Energy Efficient Bandwidth Management in Wireless Sensor Network

Dnyaneshwar, Mantri

DOI (link to publication from Publisher):
10.5278/vbn.phd.engsci.00190

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

ENERGY EFFICIENT BANDWIDTH MANAGEMENT IN WIRELESS SENSOR NETWORK

BY
DNYANESHWAR SHRIRANGLAL MANTRI

DISSERTATION SUBMITTED 2016

AALBORG UNIVERSITY
DENMARK

ENERGY EFFICIENT BANDWIDTH MANAGEMENT IN WIRELESS SENSOR NETWORK

by

Dnyaneshwar Shriranglal Mantri

A thesis submitted in partial fulfillment for the

degree of Doctor of Philosophy

in the

Department of Electronic Systems

Aalborg University

Dissertation submitted: October 26, 2016

PhD supervisor: Professor. Ramjee Prasad
Aalborg University

Assistant PhD supervisor: Professor Shingo Ohmori, CTIF, Japan,
Aalborg University

PhD committee: Associate Professor Reza Tadayoni (chairman)
Aalborg University, Denmark

Professor K.C. Chen
National Taiwan University, Taiwan

Professor K.P.Subbalakshmi
Stevens Institute of Technology, USA

PhD Series: Faculty of Engineering and Science, Aalborg University

ISSN (online): 2246-1248
ISBN (online): 978-87-7112-702-7

Published by:
Aalborg University Press
Skjernvej 4A, 2nd floor
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Rosendahls, 2016

CV

Dnyaneshwar S Mantri is IEEE student member, Life Member of ISTE, IETE and graduated in Electronics Engineering from Walchand Institute of Technology, Solapur (MS) India in 1992 and received Masters from Shivaji University in 2006. From 1993 to 2006 he was working as a lecturer in different institutes [MCE Nilanga, MGM Nanded, and STB College of Engg. Tuljapur (MS) India]. From July 2006 to 2010 he worked as an Assistant Professor and then promoted to Associate Professor in Department of Electronics and Telecommunication Engg. Sinhgad Institute of Technology, Lonavala, Pune. Currently, he is pursuing his PhD. in wireless communication at Center for TeleInFrastruktur (CTIF), Aalborg University, Denmark. His research interests are in Adhoc Networks, Wireless Sensor Networks, Wireless Communications specific focus on energy and bandwidth.

ENGLISH SUMMARY

In recent years, Wireless Sensor Networks (WSNs) is a growing era in the real-time applications. The transmission of real-time traffic over such network requires both energy and bandwidth which is scarce. In the application-based environment, all the layers of protocol stack consume energy and bandwidth for transmission of packets from nodes to sink at the cost of reduced network lifetime. This thesis examines the design of cross-layer mechanisms that are energy and bandwidth efficient using aggregation, scheduling and synchronization mechanisms. The cluster-based in-network processing mechanisms are the efficient solution to reduce the communication cost, energy and bandwidth of the network.

The data aggregation process has a trade-off between energy and delay which results in few packets or data transmissions from nodes to cluster heads (CHs). The data buffering from closer sources, collection and processing of data/packets from far away sources in the cluster are the main reasons of energy consumption and delay in the network. The research proposed cluster-based rate aggregation mechanisms, Two Tier Cluster-based Data Aggregation (TTCDA) and Grouping of Clusters (GCEDA) algorithms to increase the throughput with reduced energy consumption. The proposed algorithm applies the perfectly compressible aggregation functions on the data/packets received by CH and sink. The aggregation function considers the spatial and temporal correlation of data or packets generated by each node at a variable rate. Both the algorithms are appraised with static, mobile and heterogeneous scenarios and proposed the Mobility and Heterogeneity aware algorithm (MHCDA). The addition of heterogeneous nodes balances the energy of network to increase throughput and the network lifetime. Throughput is the measure of bandwidth utilization. The simulation results showed that the proposed aggregation algorithms reduce the communication cost, energy consumption, and the throughput hence energy and bandwidth efficient as compared with existing state-of-the-art solutions.

The bandwidth utilization of WSN also depends on the collision and retransmission of the number of aggregated packets from CHs to sink. The research proposes the Cluster-based Myopic and Non-Myopic Scheduling (CMNMS) and Schedule-based Data Aggregation algorithm with Node Mobility (SDNM) to reduce the energy consumption and increases the bandwidth utilization. These algorithms are expedient for allocating the schedules based on TDMA as basic MAC layer protocol. The schedules are decided based on the availability of free slots and the current as well as predicted future state of the channel. It works on TDMA as MAC protocol. As compared to the state-of-the-art solutions, the proposed algorithms outperform for increasing the throughput (bandwidth utilization), a decrease in delay and energy consumption.

The research also proposes Schedule-based Collision Avoidance (SCA) algorithm for reducing the collisions in multi-path data propagation and improvement in channel bandwidth utilization. The rational between reliability and energy efficiency is achieved by combination of CSMA/CA and TDMA techniques. The distinct feature of scheduling algorithms are, reduced collision and retransmission of packets due to proper slot allocation for transfer of aggregated packets from nodes to CHs to the sink.

The research also analyzed the need of synchronization algorithm for effective data collection in WSNs to increase the bandwidth utilization and proposed the Synchronized Data Aggregation algorithm (SDA). It establishes the hierarchical structure in the network using cluster-based spanning tree (SPT) mechanism and then performs the level by level synchronization. The research also proposes the hybrid (scheduling and synchronization) approach to improve the bandwidth utilization. The scheduling algorithms are used to allocate the collision-free slot, and these slots are synchronized to minimize the clock skews. It helps to reduce the synchronization errors and hence energy consumption. The level-by-level synchronization used helps to reduce the retransmission of packets and avoids collisions, improving the throughput and energy consumption. The results of Node Heterogeneity aware Energy Efficient Synchronization (NHES) algorithm in static, mobile and heterogeneous scenarios outperforms as compared to the state-of-the-art solutions.

In summary, this thesis addresses important issues of bandwidth utilizations and provides the frameworks, methods, and mechanisms based on data aggregations, scheduling, and synchronization of the nodes in the WSNs. The proposed work and solutions in this thesis may apply to ubiquitous computing networks using WSNs.

Keywords: Aggregation, Bandwidth utilization, Clusters, Collisions, Communication Cost, Energy Consumption, Throughput, Scheduling, Synchronization, and Wireless Sensor Network (WSN).

DANSK RESUME

I de seneste år er Wireless Sensor Networks (WSNs) blevet en voksende æra i real-time applikationer. Overførslen af real-time trafik over sådanne netværk kræver både energi og båndbredde, hvilket er en knap ressource. I anvendelsesbaserede miljøer forbruger alle lag af protokolstakken energi og båndbredde til transmission af pakker fra knudepunkter til opsamlingssted på bekostning af reduceret netværkslevetid. Denne afhandling undersøger design af krydslagsmekanismer, der er energi- og båndbreddeeffektive, ved hjælp af sammenlægnings-, planlægnings- og synkroniseringsteknikker. De klyngebaserede in-netværk behandlingsmekanismer er en effektive løsning til at reducere kommunikationsomkostninger, energi og båndbredde i netværket.

Data sammenlægningsprocessen har en afvejning mellem energi og forsinkelse, hvilket resulterer i nogle få pakke- eller dataoverførsler fra knudepunkter til klyngehoveder (CHs). Databuffering fra kilder tæt på og indsamling og behandling af data/pakker fra fjerne kilder i klyngen er hovedårsagerne til energiforbrug og forsinkelse i netværket. Forskningen foreslår klyngebaserede rate aggregeringsteknikker, Two Tier Cluster-based Data Aggregation (TTCDA) og Grouping of Clusters for DA (GCEDA) algoritmer til at øge gennemløb og reducere energiforbruget. Den foreslåede algoritme anvender de perfekt komprimerbare opsamlingsfunktioner på data/pakker modtaget af CH og opsamlingsstedet. Opsamlingsfunktionen tager hensyn til den spatiale og temporale sammenhæng af data/pakker skabt af hvert knudepunkt i variabel fart. Begge algoritmer vurderes med statiske, mobile og heterogene scenarier og foreslår Mobility and Heterogeneity Aware algoritmen (MHCDA). Tilsætningen af heterogene knudepunkter afbalancerer energien af netværket for at øge gennemløb og netværkets levetid. Gennemløb er et mål for udnyttelsen af båndbredde. Simuleringsresultaterne viste, at de foreslåede sammenlægningsalgoritmer reducerer kommunikation somkostninger, energiforbrug og gennemløb, og er dermed effektive med hensyn til energi og båndbredde i forhold til eksisterende state-of-the-art-løsninger.

Båndbreddens udnyttelse af WSN afhænger også af kollision og retransmission af antallet af aggregerede pakker fra CH til opsamlingssted. Forskningen foreslår klyngebaseret Myopic og Non-Myopic planlægning (CMNMS) og planlægningsbaseret datasammenlægning algoritme med Node Mobility (SDNM) for at reducere energiforbruget og øge udnyttelsen af båndbredden. Disse algoritmer er hensigtsmæssige for fordeling af tidsplaner baseret på TDMA som grundlæggende MAC lagprotokol. Skemaerne er valgt baseret på tilgængeligheden af gratis slots og den nuværende såvel som den forudsagte fremtidige tilstand af kanalen. Det virker på TDMA som MAC-protokol. De foreslåede algoritmer overgår state-of-the-art-løsninger ved at øge gennemløbet (båndbredde udnyttelse) samt et fald i forsinkelse og energiforbrug.

Forskningen foreslår også Schedule-based Collision Avoidance (SCA) algoritme for at reducere kollision i multipath data spredning og forbedring i brug af kanal båndbredde. Afvejningen mellem pålidelighed og energieffektivitet opnås ved sammensmeltning af CSMA/CA and TDMA teknikker. Det særlige kendetegn for planlægningsalgoritmer er reduceret kollision og retransmission af pakker på grund af korrekt slot tildeling for overførsel af aggregerede pakker fra knudepunkter til CH'er og opsamlingssted.

Forskningen analyserer også behovet for synkroniseringsalgoritme for effektiv dataindsamling i WSNs for at øge udnyttelsen af båndbredden og foreslår Synchronized Data Aggregation algoritmen (SDA). Den fastlægger den hierarkiske struktur i netværket ved hjælp af klynge baserede grenmekanismer og udfører derefter niveau til niveau synkronisering. Forskningen foreslår også hybrid (planlægning og synkronisering) tilgang for at forbedre udnyttelse af båndbredden. Planlægningsalgoritmer bruges til at allokere kollisionsfri slot, og disse slots er synkroniseret til at minimere måleforvrængninger. Det hjælper til at reducere synkroniseringfejl og dermed energiforbruget. Den anvendte niveau til niveau synkronisering hjælper til at reducere retransmission af pakker og undgå kollisioner, forbedre gennemløb og energiforbrug. Resultaterne af Node Heterogenity-aware Energy Efficient Synchronization (NHE'er) algoritme i statisk, mobil og heterogen scenarie overgår state-of-the-art-løsninger.

Sammenfattende omhandler denne afhandling vigtige spørgsmål om båndbreddeanvendelser og giver rammer, metoder og teknikker baseret på dataopsamling, planlægning og synkronisering af knudepunkterne i WSNs. Arbejdet og løsningerne i denne afhandling kan gælde for allestedsnærværende datanetværk, som bruger WSNs.

Nøgleord: opsamling, båndbreddeudnyttelse, klynger, kollisioner, kommunikationsomkostninger, energiforbrug, gennemløb, planlægning, synkronisering, og Wireless Sensor Network (WSN).

.

ACKNOWLEDGEMENTS

"God acknowledges me something I wanted, but he gave me everything I needed." I express my deep sense of gratitude and respect to my guide Prof. Ramjee Prasad, Director, CTIF, Aalborg University, Denmark for his valuable guidance and encouragement to refine and direct the work experience with the ideas presented. It has been a pleasure for me that I have got an opportunity to work under a highly reputed and well-disciplined personality.

"Fill the brain with high thoughts, highest ideals, place them day and night before you, and out of that will come great work." I am always obliged to Dr. Neeli Rashmi Prasad, without her support and guidance, it was not possible to complete the work.

Its pleasure for me to express sincere thanks to Dr. Rasmus Hjorth Nielsen for guiding and helping me in this work. Dr. Rasmus has helped me in the formulation of the problem and decide the path. I am very much thankful to him for his cooperation.

I express my sincere gratitude towards co-supervisor Dr. Shngo Ohmori for guidance and support.

I am also thankful to staff of Electronics System Department and CTIF, Aalborg University, Denmark for timely help and cooperation.

I am predominantly thankful to the Management of Sinhgad Technical Education Society, Pune. I am indebted to Honorable founder president of STES, Prof. M. N. Navale, Founder Secretary of STES, Dr. Mrs. S. M. Navale. Vice-president (HR), Rohit M. Navale, Vice-president (Admin), Rachana Navale. The Institution has provided a doorstep opportunity to enhance technical knowledge and upgrade the qualification with full funding.

I offer my respects to Dr. S. S. Inamdar - the source of inspiration, Dr. M.S. Gaikwad- strong supporter, Dr. A.V. Deshpande- Motivator, Dr. D. S. Bormane and Dr. R. G. Tated–well-wishers and supporters, and all my GISFI fellow colleges and department staff of SIT. My special appreciation and thanks to Pranav and Nandkumar.

My special thanks to Mrs. Jyoti Prasad, Mr. Rajiv Prasad and Mrs. Mayuri Prasad for making my stay much comfortable with their love and support. Their affection and care were memorable.

Finally, I acknowledge blessings of father Shriranglal, mother Gangabai brother Panduring with family. I recognize the encouragement, moral support, and motivation provided by beloved life partner Ritu, sweet daughter Shreya, and son

Atharva from the bottom of the heart, their smile always helped me to come out of difficulties – Good Motivators. They are not only supporter but are the creators.

Last but not the least, I would like to thank all helping hands involved in the journey of thesis and research work. “Desire is the key to motivation, but determination and commitment to excellence will attempt you to success.”

Mr. MANTRI D .S.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

Acronyms	**Abbreviations**
WSN	Wireless Sensor Network
CH	Cluster Head
DA	Data Aggregation
LA	Local Aggregator
EBWM	Energy Efficient Bandwidth Management
WMN	Wireless Mesh Network
MLH	Multi-Hop Length
QoS	Quality of service
IoT	Internet of Things
BS	Base Station
Agg.	Aggregation
PDR	Packet Delivery Ratio
PGR	Packet Generation Rate
TDMA	Time Division Multiple Access
CSMA	Carrier Sense Multiple Access
FDMA	Frequency Division Multiple Access
CDMA	Code Division Multiple Access
MAC	Medium Access Control
TTCDA	Two Tier Cluster-based Data Aggregation
EECDA	Energy Efficient Cluster-based Data Aggregation
GCEDA	Grouping of Clusters for Efficient Data Aggregation
LEACH	Low-energy Adaptive Clustering Hierarchy
ER	Equal Rate
DR	Different Rate
NWL	Network Lifetime
RT	Response Time
ACO	Ant Colony Algorithm
GRASS	Grid-based Routing and Aggregator Selection Scheme
LEO	Least-Time Energy-Efficient One-Level Data Aggregation.
PDA	Privacy Data Aggregation
EEIA	Energy Efficient In-network Aggregation
DyDAP	Dynamic Data Aggregation for Privacy-aware WSN
ADA	Adaptive Data Aggregation
CWCG	Cluster-Wide Correlated Grouping)
CTEPEDCA	Cluster-based and Tree-based Power Efficient Data Collection and Aggregation Protocol
CPDA	Cluster-based Private Data Aggregation
BECPA	Bandwidth Efficient Cluster–based Packet Aggregation
BECDA	Bandwidth Efficient Cluster–based Data Aggregation
SEP	Stable Election Protocol
EDGA	Energy-efficient Data Gathering Protocol

MARWIS	Management Architecture for Heterogeneous WSN
MHBCDA	Mobility and Heterogeneity aware Bandwidth Efficient Cluster-based Data Aggregation
SCT	Semantic Correlation Tree
CM	Cluster Members
CMNMS	Cluster-based Myopic and Non-Myopic Scheduling
GCF	Green Conflict Free
TPSN	Timing-Synch Protocol for Sensor Networks
SDNM	Schedule based Data aggregation with Node Mobility
SCA	Schedule based Collision Avoidance
GTS	Guaranteed Time Slot
DRAND	Distributed Randomized TDMA Scheduling for Wireless Ad-Hoc Networks
A-DRAND	Adaptive DRAND.
DMP	Dynamic Multilevel Priority
CP	Communication Period
CAP	Contention Access Period
CFP	Collision Free Period
CCA	Clear Channel Assessment
SDA	Synchronized Data Aggregation
DATP	Distributed Time Scheduling Protocol
BESDA	Bandwidth Efficient Hybrid Synchronized Data Aggregation
SPT	Spanning Tree Mechanism
MHS	Mobility-aware Hybrid Synchronization
NHES	Node Heterogeneity-aware Energy Efficient Synchronization

CHAPTER 1. INTRODUCTION

The main objective of this chapter is to explain the motivation, background, and challenges leading to bandwidth management in Wireless Sensor Networks (WSNs). Key issues and modules for bandwidth management frameworks are explained to get the in-depth synopsis of the thesis. The chapter identifies the research questions and proposes the methodology to solve them. The scientific contributions of this thesis are explained, and the details of related publications are provided. Finally, an overview of the individual chapters of the thesis is outlined.

1.1. INTRODUCTION

Data collection and processing is the important feature of the WSNs used in the widespread applications considering real-time data analysis as *"e-agriculture, habitat monitoring, vehicular technology, health-care, military, smart homes and environmental monitoring and control [1-2]."* In all these use-cases, data generated is uneven and node has to report the reading of the sensed event to sink. However, the resource-constrained nature of the nodes restrict the processing, storage, and communicating capabilities [1-7]. The data processing capacity of the WSNs depends on the number of nodes used in the formation of the network. The generated data is huge and need the pre-processing as aggregation to reduce repetitive multiple copies of data, by minimizing the redundancy. Accordingly, the way of aggregation in the structured network showing variation in the network topology is influenced by energy consumption, network lifetime and communication bandwidth of the WSNs [4-5, 7]. In WSN, the cluster-based aggregation is predominantly preferred over flat since it improves the performance of scalable network by stabilizing the network topology [6-7]. Also, the network remains operational even if one CH fails maintaining a lower delay in short range transmissions of data or packet from node to the CH and have simple routing structure. To save the energy, improve the network lifetime and bandwidth utilization, the aggregation function (min, max, avg, sum, count, median, etc.) used at CH reduces the redundant data to be transmitted from the source node to sink [7, 35]. *"In the hierarchical WSN, resource allocation is related to the amount of bandwidth given to the CH, which may act as a router in the network [7]".* Also, a major technical challenge in WSN lies in node energy constraint. Under static conditions, the data packets transmitted by nodes are aggregated at CH. Also, each CH sends several copies of aggregated data directly to sink which increases energy consumption in communication rather than sensing and presents the fundamental limit on network lifetime of WSNs. The maximizing network lifetime with data gathering considers the optimal tree, where CH in route may act as an aggregator or simply forward the data. The current research trend in cluster-based data aggregation is to minimize the trade-off between energy, delay and throughput at the sink in correlation with bandwidth utilization [7].

1.2. MOTIVATION AND NEED

WSNs are application based and has a number of nodes distributed in a random manner forming infrastructure-less architecture to sense the event of interest. With increased node density in the network, an independent communication of sensed data to the base station or sink causes congestion. The excessive traffic at sink node may increase the response time and loss of packet and data. Packet and data loss is caused due to resource constraint nature of the node such as low bandwidth, low memory, and a small battery. It directly effects on the performance of the network with energy consumption and network lifetime. Also, improper utilization of bandwidth causes the congestion and loss of data [7]. It demands the scheme to be developed for reducing the congestion by minimizing the redundant data and improve the Quality of Service (QoS) parameters of WSNs as energy, delay, lifetime and bandwidth utilization. The bandwidth utilization is correlated with measurement of throughput.

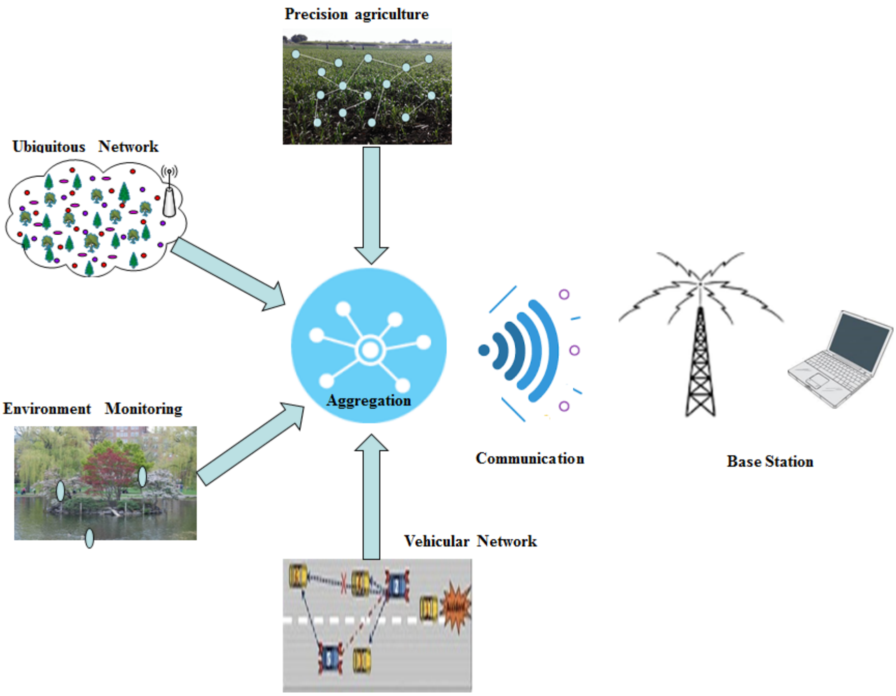


Figure 1- 1 Aggregation scenario in WSN

Figure 1-1 illustrates aggregation scenario representing the need for bandwidth management in WSN. In all,

- Wireless Sensor nodes have the unique capability of transmission at different power levels. With variation in transmission power, a trade-off exists between a number of hops and overall communication bandwidth available to individual nodes.
- Real-time applications require guarantees reduced end to end delay for improvement in throughput.
- As traffic introduced into the network is in the form of events, may cause congestion and leads to inefficient resource utilization [energy and bandwidth].

1.3. RELATED WORKS

The state-of-the-art represents an overview of different strategies and protocols used for energy efficiency bandwidth utilization in WSNs. These are classified according to data aggregation methods, bandwidth allocation mechanisms, scheduling and synchronization algorithms.

In-network processing and aggregation [3], the data aggregation protocols used for bandwidth utilization can be classified according to the structure used for the formation of the network; some protocols use in-network processing for the aggregation of data. This approach is suitable for the stationary nodes but needs special considerations for the mobile nodes. In [4-7] author proved that the data-centric routing approach is better than address centric for the aggregation of information. It shows that the performance is greatly affected by the placement of sink and sources when the density of nodes in the network increases. It focuses on the tree and different cluster-based algorithms used for data aggregation. [8] Presents the survey of resource allocation, scheduling, and TDMA protocols for efficient utilization of bandwidth. According to the survey, star and mesh topology consumes more bandwidth as compared to the cluster. Clustered networks with TDMA slot allocation helps to improve the bandwidth utilization. [9] Presents the solution for utilizing the available bandwidth when real-time events are considered. It proposes the 802.15.4 based MAC protocol to reduces the uncertainty under overload conditions but not suitable for dense networks. In [10], author explained time-slotted, scheduled MAC algorithm by clustering the nodes in different frequency domains. It proposes the hybrid approach for utilizing the bandwidth by allocating the TDMA slots in the frequency domain. The network provides high connectivity but due to limited time slots, the capacity of network degrades. [11] Presents an approach for bandwidth allocation by time-frequency slot allocation to the nodes. Due to this approach network capacity increases with reduced channel interference. It considers the frequency reuse factor but has the drawback of time synchronization. It exploits the relationship between bandwidth and energy efficiency to increase the network lifetime. [12] Focuses on the real-time applications where single hop routing does not satisfy the time requirement.

Table 1- 1 Comparison of data aggregation algorithms

Protocol	Topology and Agg. approach	Parameters	Sched uling	Sync Control	Pros	Con
EEIA [5]	Tree, Indexed Routing	Remaining power on each node,	No	No	Considerable power saving and increased	Requires maintenance of index table for nodes with fewer thresholds. It
GRASS [14]	Tree, In- network Agg + routing	Network lifetime, energy and latency, Overlap Agg.	No	No	Reduces the overload due to less Agg. Points	Selection of Agg. Node is difficult, need synchronization.
ACO [115]	Tree, Routing-hop count	Initial delay is high finding the path, energy	Yes	No	Reduced energy costs.	Source node near the sink cannot aggregate the data packet Requires more runs
LEO [16]	Tree, shortest path, event driven	Network lifetime, and energy efficiency	No	No	Ensures reliability and congestion avoidance. Reduces the computational	Does not support mobility and heterogeneity of node
CPDA [17]	Cluster, Min/Max Agg.	Privacy preserving efficiency, accuracy, and computational overhead	No	No	Reduced communication overhead	High computational complexity due to bidirectional links
ADA [18]	Cluster, Event driven	Reliability, temporal and spatial Agg. Sensing range.	No	No	Reliable aggregation points	Not scalable for dense WSN Performance affects with sensing range.
DyDAP [19]	Cluster, Privacy and end to end security	Transmission buffer overflow, estimation accuracy and energy efficiency.	No	No	Provides better estimation of accuracy with reduced buffer size, avoid congestion.	The resources need to be powerful and computational

The problem can be solved using linear path programming approach. The sender decides which packets will be dropped according to rate allocation, but this will have a problem of reliability due to correlated packet dropping. Management architecture for heterogeneous WSN (MARWIS) [13], proposed for continuous monitoring application. The network is divided by a node of the same type in one group, and a wireless mesh network (WMN) operates as the communication gateway between these group of nodes. Thus, round trip time is reduced. It has the problem of synchronization of nodes to minimize energy consumption. The performance comparison of different tree and the cluster-based algorithm is given in Table 1-1 [5, 14-19]. In [20], the trade-off between aggregation throughput and gathering efficiency is presented with a single hop and multi-hop length schemes. The aggregation is achieved using a perfectly compressible function which shows MLH scheme is scalable. In [21], the author proposed the hybrid aggregation architecture with static tree-based structure and dynamic cluster-based structure. It helps to improve the error probability and transmission cost by grouping the number of nodes into spatial and temporal correlation but affects the performance, if a number of group increases. In [22], sink node gets the maximum information by considering the deadline constraint to achieving energy delay trade-offs. It improves the quality of data received but incurs data loss. The author considers the one-hop tree structure and interference model with a deadline imposed by the sink. In [23], the hybrid approach of selecting the data aggregation points dynamically switch depending on the threshold of data traffic from static to dynamic. Static clustering has the advantage of increasing the energy efficiency, but dynamic clustering improves the bandwidth utilization.

From the survey, data aggregation mechanisms are used to provide the effective bandwidth utilization when the density of node in the network increases. The factors affecting on the data aggregation algorithms are; network topology, formation of the cluster, election of CH, node deployment, heterogeneity of nodes, mobility patterns, traffic patterns, transmission media, link quality and aggregation methods, etc.

In [24], an aspect of data aggregation is considered by delay performance with link scheduling and node specific interference models. This approach is suitable for small network size. [25, 26] consider the MAC protocol using combination of TDMA and CSMA techniques for scheduling the data and control messages. The frame size used for data and control message is varied according to changing traffic condition and mobility of nodes in the network. It gives the detailed requirement of TDMA protocol used for improving the energy efficiency. In Adaptive DRAND (A-DRAND) [27] with increased node density it difficult to maintain the energy balance in the network. For collision-free data transfer CH is assigned more slots, while other members alter the role of CH after specified time interval to balance the energy. This reassignment of slots increases the overheads. In [28], presents the use of TDMA MAC protocol for short range data communication with little overheads and communication errors as compared to CSMA. The factors that affect in the allocation of conflict-free slots are, network topology, traffic introduced by nodes, mobility of nodes and sink, collision of packets, the MAC used for allocation of slots, adjusting sleep/wake-up times of the nodes. Ref [29-31], gives the different ideas to develop the bandwidth utilization strategies as rate control, load balancing and network coding.

Time and clock synchronization is critical in WSN and represents the primary challenge in aggregating the effective data and scheduling the slots for improvement in bandwidth utilization. In [32-34], a survey of different synchronization algorithm is presented with a focus on synchronizing and scheduling the functionalities of the nodes with the reference clock of the network, since the clocks of nodes used in WSN operates independently. If nodes in the network are not synchronized, then information integration and interpretion is difficult. Also, topological variations caused due to mobility and scarce resource of nodes as bandwidth restricts the multi-hopping and demands for new solution differing from traditional ones having the capability of estimating the time uncertainties accurately.

From the survey in related work, the present algorithms used to reduce the energy consumption and bandwidth utilization lack in the selection of CH, selection of aggregation points, allocating conflict–free slots, congestion avoidance, application of scheduling, and synchronization controls, reducing computational and communication load in the network with mobile nodes. Hence, to address these challenges for improving network performance with special focus on energy and bandwidth utilization, an energy efficient bandwidth management framework for WSN is proposed in the research work.

The proposed data aggregation algorithms in [35-42] show improvement in throughput and energy consumption. The aggregated data is sent to the sink with conflict-free scheduling algorithms proposed in [43-45] and nodes synchronization strategy presented in [46-50] helps to reduce the errors and increase in throughput.

1.3.1. OPEN ISSUES AND PERFORMANCE METRICS IN WSN

The open issues and performance measurement factors that greatly effects on the development of application specific WSNs are,

- **Topology Control:** The performance of network depend on the topology used. Star and mesh topology consumes more energy and bandwidth as compared to the cluster. Also, the mobility of nodes in the network continues to change the network dynamics demanding more energy. The algorithm needs to inculcate these changes for sustaining the overheads and network stability.

- **Traffic Management:** WSN are infrastructure-less network and the traffic generated by the nodes is bursty in nature. It requires the appropriate routing path to communicate the sensed information in terms of packets to sink. If traffic increases then, the bandwidth requirement also increases, thus the need to propose effective bandwidth utilization mechanisms.

- **Clock Synchronization:** The synchronization algorithms used introduces the time drift causing overheads and errors. It consumes significant energy due to miss-match of the clock. Also, packet gets collide and need retransmission causing more bandwidth requirements. A synchronization algorithm needs to reduce the overheads and clock drifts and utilize the available energy and bandwidth efficiently.

- **Scheduling:** The important requirement of reducing the energy consumption is proper allocation of conflict-free slots. It avoids the collision and retransmission of data. Slots are allocated by considering TDMA scheduling which improves the throughput.

- **Energy Efficiency:** It depends on the amount of data gathering and the functionality of the nodes used in aggregation and retransmission of packets. It also depends on the failure of the relay nodes in the path from source to sink. When the energy of a node is drained due to continuous monitoring, network dynamics change and reduces the lifetime of the network.

- **Latency:** Delay is one of the prime concerns in data aggregation mechanism. It depends on the one hop or multi-hop communication, number of collisions in channel and depth of aggregation tree.

- **Throughput:** It is a measure of the aggregated information at the CH or sink. It depends on the aggregation methods, allocation of slot and synchronization of nodes. It has a direct impact on the link bandwidth.

- **Bandwidth:** Nodes used have very low bandwidth and cannot outfit for real-time applications. If the nodes in WSN generates busty-traffic, it demands more bandwidth for enhanced performance of the network. The bandwidth utilization mechanisms need to be developed according to the variable traffic (packet generation rate) from the nodes. We can correlate the throughput with bandwidth utilization– collision avoidance.

- **Network Lifetime:** It depends on the how much energy is drained in the transmission of broadcast messages for formation of cluster, election of CH, data gathering and scheduling activities of nodes. It also depends on the nodes contending for channel accesses.

- **Coding and compression of data:** Redundant data from nodes is one of the reasons of consuming more energy and bandwidth. Source coding is one of the ways to reduce the redundancies in the sensed data while channel coding increases the reliability. The way of compression of data is important.

- **Mode of communication (single or multi-hop):** To increase the throughput and reduce the energy consumption one-hop communication is preferred but consumes more bandwidth within the cluster. During network-wide communication, it is better to use the multi-hop, since the direct transfer of data from node to sink will require more energy.

- **Security:** Adding security to aggregated data is a critical task. It needs to increase the usability of the channel with minimum attacks.

- **Mobility and heterogeneity:** The mobility of node or sink frequently changes the network dynamics causing increased energy and bandwidth requirements for finding the optimal path. However, it has the benefit of increasing the throughput with reduced delay. By adding the nodes with a different energy, network sustains more and increase the lifetime.

The network and node level challenges are given in Table 1-2

Table 1- 2 Node and network level operational challenges

Node level	Network level
• Energy constraints • Limited storage and computations • Scalability • Clock synchronization • Low bandwidth • High error rates	• Energy-efficiency at all layers • Data aggregation • Scheduling • Time synchronization • Node placements (localization) • Network scalability • Self- organized routing • Data dissemination

1.3.2. BANDWIDTH MANAGEMENT MECHANISMS

WSNs are application-specific, and data collecting nodes from events of interest are scarce in the resources like bandwidth, energy and storage capacity. If communication of data packets is direct, it may cause the loss of data due to flooding at the CH or sink, less availability of required communication bandwidth, the collision of packets, change of traffic patterns, the decision on data processing and finding optimal route. The reliable communication of data to CH or sink demands more bandwidth which is scarce in WSNs. The current bandwidth management mechanisms focus on the physical layer parameters to optimizing its utilization. The modulation and coding schemes give solution for increasing the throughput and energy saving in the wireless networks. However, theses mechanisms may not fulfill the requirements of WSN, since nodes used for formation of the network are resource constrained. As WSNs are event-based and generate the multiple data, it necessitates the need for an effective strategy which will provide the appropriate solution for utilization of bandwidth with reduced energy consumption for the sustaining network. Figure 1-3 shows the different approaches used for effective bandwidth utilization.

Data Aggregations: The basic purpose of data aggregation algorithms is to reduce redundant data form nodes with in-network processing. It reduces the energy requirement and the communication cost. The factors affecting on the data aggregation algorithms are; network topology, formation of the cluster, the election of CH, node deployment, heterogeneity of nodes, mobility patterns, traffic patterns, transmission media, link quality and aggregation methods. The in-network processing and data management have a trade-off between computation and communication complexity [3-5, 7].

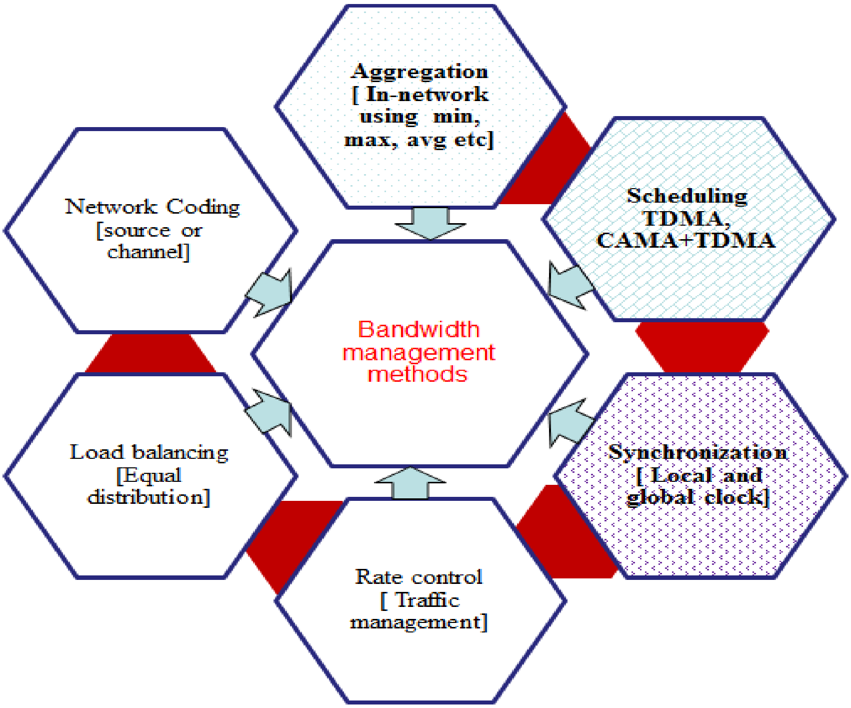


Figure 1- 2 Bandwidth management mechanisms

Distributed Frequency Slot Assignment: It uses the cluster-based approach with tree topology and faces the problem of synchronization. The time-frequency slot assignment approach gives a good result for the same type of clusters and differs for different cluster formation strategies. Nodes in the network have individual time-frequency slot for packet communication instead of allocating a band of frequency to the cluster. Due to individual slot allocation bandwidth requirement increases [11].

Slotted Time Approach: TDMA or fusion of TDMA and CSMA- in this approach guaranteed time slot is considered but faces the problem of bandwidth wastage, if the node does not have data to transmit. It is not suited for the multi-hop communication. Bandwidth utilization is also affected by the network density. The hybrid approach helps to improve the network performance [10, 26].

Schedule-Based Approach: It faces the problem of adjusting sleep time and synchronizing the slots. The metrics used for improving network performance are, buffer management, duty cycle adjustment for sleep and wake-up time of node, management of data flows according to the availability of the channel, collision avoidance, etc. Scheduling fails when the data available to transmit is high and wastes the bandwidth [8, 25].

Synchronization Controls: Un-synchronized network increase the overheads and errors in matching the clocks of nodes with the reference clock of the network. It consumes more energy and performance degrades. Spanning Tree-based synchronization helps to reduce the synchronization errors occurred due to clock drifts and increases the throughput [8, 46-47].

Rate Control Approach: It is considered according to the traffic introduced in the network. If real-time traffic is introduced, it must restrict to its packet transmission rate according to the allocated share. The rate control can be done at various layers of the protocol stack. A network with increased data and fixed bandwidth causes the congestion and has a direct impact on energy, packet service time, and throughput. The fair sharing of bandwidth is decided according to variation in network traffic and congestion control mechanisms. The congestion control technique reduces the energy consumption and improves the channel quality [29].

Load Balancing Approach: It is based on the distribution of the number of nodes in each cluster with same characteristics. Configuration and the equal-sized cluster are crucial for extending the network lifetime. Even distribution of nodes leverages the data delay [30].

Network Coding: This approach is used to encode the data for reliable communication of packets. Channel coding theorems reduce the error probability with an increase in the throughput. Distributed source coding is one of the major concerns [31].

These schemes may be incompatible with some of the techniques that rely on promiscuous packet reception to improve the bandwidth usage. A detailed study of the trade-off between bandwidth efficiency and energy efficiency in the shared medium of WSNs is an important task and taken throughout the research work.

1.4. BANDWIDTH MANAGEMENT FRAMEWORK

The objective of this research is to develop an energy efficient bandwidth management framework for resource constrained WSNs. The bandwidth and energy constraint of the node has a direct impact on QoS and efficiency of WSNs. The bandwidth utilization is affected by the performance metrics used by the physical, data link and network layers of WSN protocol stack. Therefore, a need arises to develop a cross-layer abstraction for improving the network performance with metrics as energy consumption, network lifetime, delay, bandwidth utilization, and computational overheads in WSNs. The three building blocks (Aggregation, Scheduling, and Synchronization mechanism) of an energy efficient bandwidth management framework are shown in Figure 1-3,

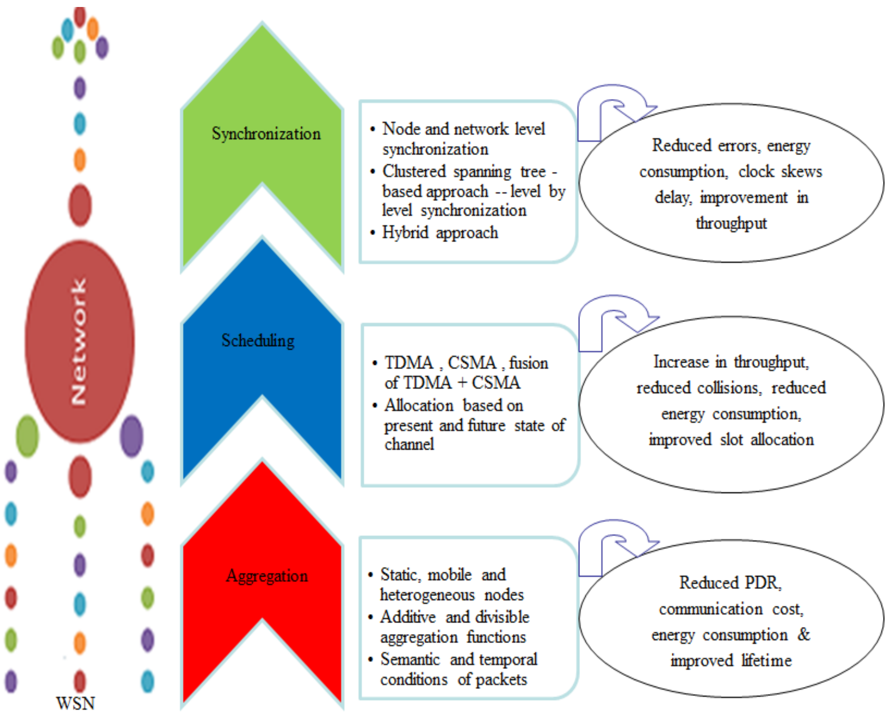


Figure 1- 3 Bandwidth management framework- building blocks

According to the challenges mentioned in section 1.3 and 1.3.1, the research problem is divided into subproblems by considering the static node and sink, varying node and sink mobility, node heterogeneity with varying traffic intervals in the network.

- Propose the cluster-based data aggregation model to reduce the redundancies in received data (packet count), energy consumption and improving the bandwidth utilization and network lifetime.

- Propose the conflict–free scheduling mechanism for reducing collisions, the energy consumption and improving the throughput based on the availability of channel bandwidth.

- Propose the optimized synchronization mechanism for reducing errors and clock skews to improve the bandwidth utilization and energy consumption.

1.5. RESEARCH METHODOLOGY

The research is motivated by the current literature in bandwidth utilization by use of rate-based approach, load balancing at upper layers and so on. Very little work has been addressed by use of cross-layer approach (MAC + Network) with a focus on aggregation, scheduling and synchronization of nodes and network under mobile and heterogeneous scenarios. The thesis compares the performance evaluation of existing mechanisms and proposes the solution to mitigate the problems in developing a novel bandwidth utilization mechanisms for cluster-based static, mobile and heterogeneous nodes in WSNs.

1.5.1. RESEARCH HYPOTHESIS

Based on the related works and challenges including requirements, the research hypothesis has been identified for developing an energy efficient bandwidth management framework for WSN. A comprehensive hypothesis comprises of,

a. Rate–based data aggregation with perfectly compressible aggregation function reduces the energy consumption, bandwidth utilization with improvement in the network lifetime.
b. Addition of mobile and heterogeneous nodes in the network improves the communication cost and the channel utilization in the WSNs.
c. Conflict–free scheduling algorithms improves the performance of WSNs in mobile scenarios with reduced energy consumption, delay and bandwidth requirements.
d. Hybrid synchronization mechanism using cluster-based spanning tree reduces synchronization errors, energy consumption and delay with increased throughput.

The hypothesis made for developing an efficient bandwidth utilization framework for WSN addresses the consideration and assumption. Therefore, research gives answers to the following questions throughout the thesis.

1. Will aggregation methods help to reduce the communication cost and mitigate the problem?
2. How scheduling is helpful in bandwidth utilization of WSN.
3. The role of synchronization algorithms in bandwidth utilization of WSN.
4. Will it be a cross-layer abstraction to develop the framework?
5. Can a proposed set of solutions help to mitigate the problem of bandwidth utilization in WSN?

1.5.2. METHODOLOGY OVERVIEW

The goal of the thesis is to develop an energy-efficient bandwidth management framework for WSNs. The principle contribution of the work is focused on data aggregation, scheduling, and synchronization mechanisms for effective utilization of bandwidth in cluster-based static, mobile and heterogeneous WSNs. The outline of research methodology is given in Figure 1-4 showing challenges, building blocks, outcomes and addressing layer.

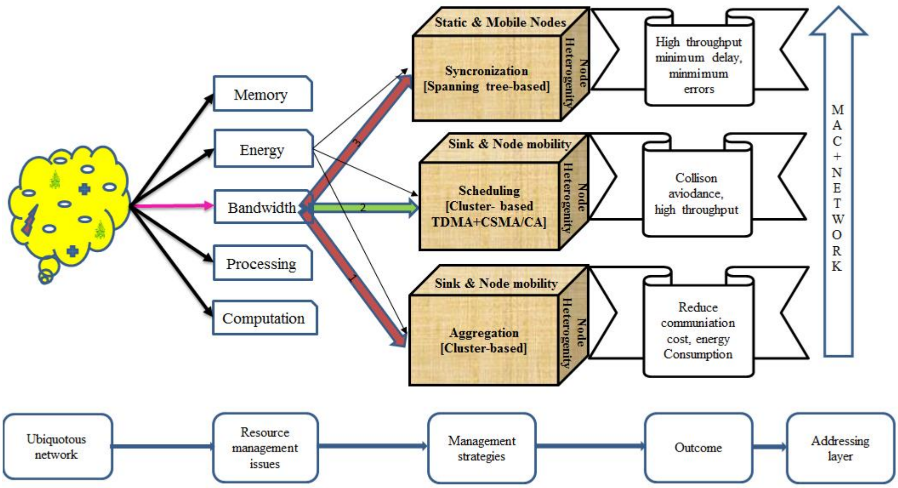


Figure 1- 4 Evolution of problem statement

The new bandwidth management framework will consider the three phases of abstractions to solve the problem. The results of each phase have given the motivation to address the next phase in a better manner. The first phase of research have found the gaps in the available approaches for aggregation and developed a simpler and understandable cluster-based aggregation model with static, heterogeneous nodes and mobile sink for packet and data aggregation. The perfectly compressible aggregation function applied at CH and Sink based on semantic and temporal correlation of packets generated at variable rate shows reduced communication cost and energy consumption, improves lifetime and throughput of the network.

The aggregation scenario has motivated to extend the work in the direction of scheduling and synchronization for an increase in the channel utilization. The schedule-based approach uses the conflict–free slot allocation for transfer of aggregated packets based on the myopic and non-myopic state of the channel. The conflict-free slot allocation using TDMA as basic MAC layer protocol reduces the collision of packets avoiding the need of retransmission hence saves the energy, reduces the delay and increases the throughput [47]. The research also continued in the direction of reducing the collision by combination of TDMA and CSMA/CA techniques. The evaluation of proposed algorithms with static and mobile scenario shows improved performance as compared to State-of–the-art solutions.

The final phase of research proposes the hybrid (scheduling and synchronization) synchronization algorithm based on the clustered SPT mechanism. Scheduling algorithms are used to allocate the conflict-free slots while synchronization algorithms synchronize them with timescale provided by reference nodes. Also, the clock skews are reduced by synchronizing the node clock with reference node in the network. The level-by-level synchronization used in the network with static, mobile and heterogeneous nodes reduces the synchronization errors, energy consumption, delay with improvement in throughput which is a measure of bandwidth utilization.

The performance of each phase is evaluated using theory assisted designs and comparative simulation by use of Matlab and NS-2 simulator.

In summary, the research outcome of the Ph.D. thesis are:

1. Data aggregation algorithms: Based on clustered network for improving the communication cost, energy consumptions and throughput.

2. Scheduled algorithms: For conflict-free slot allocation based on the state of the channel, Improving energy consumption, delay and throughput- a measure of bandwidth utilization.

3. Synchronization algorithms: The synchronization of node and network clock minimize clock skews which reduce errors, energy consumption and increase the throughput: under static and mobile environments.

4. Hybrid approach (scheduling + synchronization) to improve the throughput with reduced energy consumption.

1.6. CONTRIBUTIONS

The purpose of this thesis is to design an efficient framework for management of scarce resource of the node used in WSN as energy and bandwidth. The factors that influence the performance of bandwidth management mechanism are: changing network topology, packet generation rate, selection of aggregation points, the mobility of nodes and sink, allocation of slots and synchronization of nodes in the network. The research address the challenges specified and has a contribution in finding out the improvements in the performance parameters as energy consumption, delay, throughput (a measure of bandwidth utilization), lifetime and computational overheads for resource constrained WSNs. The contribution of the thesis is divided into three modules as aggregation, scheduling and synchronization mechanisms shown in Figure 1-5.

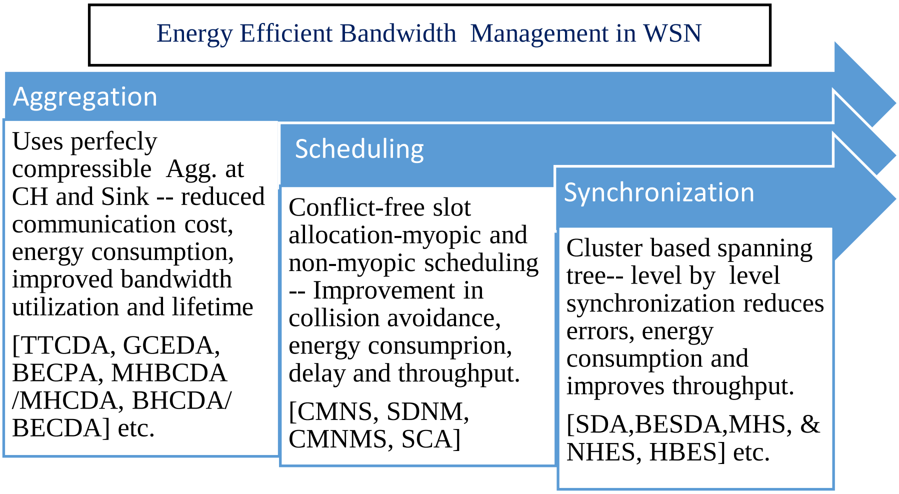


Figure 1- 5 Thesis contribution

1. Aggregation mechanism:

The efficient way of collecting the information in the network with reduced redundancy is called data aggregation. It is one of the important mechanism to provide an improvement in network parameter of resource constrained WSNs as energy, bandwidth and communication cost. The detailed survey shows that, the process of data aggregation is affected by the density of node, network topology, formation of cluster, election of CH, node deployment, heterogeneity of nodes, mobility and traffic patterns, transmission media, link quality and aggregation methods.

To address the challenges, the research proposed the cluster-based data aggregation algorithm work on two levels as intra and inter-cluster aggregation. The election of

CH based on the region, adding heterogeneity to nodes, sink mobility and the proposed perfectly symmetric aggregation function at CH and sink remove the redundant data and shows improved performance. The aggregation functions are applied according to the semantic (equal) and temporal (different) conditions of data and packets generated by the nodes at a variable rate and show reduced energy consumption, communication cost, improved throughput, and lifetime [7]. The aggregation algorithms developed considers the network with static and heterogeneous node and mobile sink. This module has six contributions depending on the methods used and network conditions. Two Tier Cluster-based Data aggregation (TTCDA) [7, 35] algorithm consider the network with random distribution of static nodes and sink. The elected CHs perform the additive or divisible aggregation function on the packets and data generated by nodes at a variable rate. TTCDA reduces the computational and communication overheads and saves energy showing increased lifetime. Grouping of Clusters for Efficient DA (GCEDA) [36] consider the grouping of nodes in the cluster based on packet generation capability and grouping of CHs with aggregated packets in the inter-cluster communication reduces the energy consumption by 14.94%. However, with variation in the number of CHs in the group and increased network diameter, energy consumption increases by 1% this causes due to the integration of packets from lower level to higher and failure of a communication link with an increase in diameter.

The mobility of sink experience frequent changes in the aggregation points but the predefined route with heterogeneous nodes in the network shows increased lifetime, reduced communication cost, throughput and packet delivery ratio. Bandwidth Efficient Cluster-based Packet Aggregation (BECPA) [37-38] algorithm takes advantage of the static sink and heterogeneous nodes for aggregating the packets generated by nodes and random data within the packet. The perfectly compressible aggregation function at CH and sink shows reduced PDR, throughput and energy consumption, hence less consumption of bandwidth as compared to EECDA. Mobility and Heterogeneity aware Cluster-based DA (MHBCDA and MHCDA) [39, 40] algorithm uses the mobile sink with the predefined region for aggregation of packets. An equal number of heterogeneous nodes with variation in energy improves the network lifetime. The packets generated at an equal rate and different rate is aggregated at CH. The nodes with equal packet generation rate use the average function while different rate uses sum function. Sink for final aggregation uses the perfectly compressible aggregation function as discussed above. Bandwidth Efficient Heterogeneity-aware Cluster-based Data Aggregation (BHCDA and BECDA) [41, 42] works on the mobile sink and heterogeneous nodes in the networks. It considers the PDR and throughput as metric of bandwidth computation with reduced energy consumption. It works on the data within the packets generated using random function in the range of 0 and 1. The performance is also compared with EECDA and TTCDA with the conclusion that BECDA is bandwidth efficient and TTCDA is energy efficient. The contribution concludes with the comment that packet aggregation is better than data aggregation for efficient utilization of bandwidth using in-network aggregation. The addition of heterogeneous nodes and providing mobility to sink, the performance of the network improves with communication cost, bandwidth utilization, network lifetime and reduced energy consumption.

2. Scheduling Mechanism:

In WSNs, communication delay and energy consumption are prime factors and depends on the collisions of multipath data propagation, and reception of more than one packet from nodes at CH and sink at the same time. A major problem occurs due to buffering of packets and non-availability of the slots confirming retransmission of packets, and time required to switch from present to predicted future state consuming more energy and bandwidth. Scheduling algorithms are required for finding efficient schedules to allocate conflict-free slots for nodes and CHs to communicate. It is an important building block for energy efficient bandwidth utilization mechanism. The scheduling algorithms proposed in this contribution works on the myopic and non-myopic state of the channel and are pragmatic for allocating the schedules based on TDMA as basic MAC layer protocol. The thesis contributes with four cluster-based scheduling algorithms. First, Cluster based Myopic Scheduling (CMNS) [43] based on the static node and sink. The packets are scheduled in the consecutive slots allowing nodes to sleep until particular time. Second, an Efficient Schedule-based DA using Node mobility (SDNM) [44] algorithm minimizes the collision of packets in the channel. The slot allocation for transfer of aggregated packets is by the availability of the channel. It shows increased overheads causing increased energy consumption as compared to CMNS but have increased throughput. Third, Cluster based Myopic and Non-myopic Scheduling (CMNMS) based on the sink mobility. Simulation results show that the performance of scheduling algorithms is improved by reducing a number of conflicts, energy consumption, delay and an increase in throughput with CMNMS as compared to CMNS and SDNM and with state-of-the-art solutions. It is also concluded that myopic scheduling works better for intra-cluster while non-myopic for inter-cluster communication. SDNM is bandwidth efficient as compared to CMNS and CMNMS. The final contribution is Scheduled Collision Avoidance (SCA) [45] algorithm- A hybrid approach of scheduling is used for reducing the collisions by fusion of CSMA and TDMA scheduling algorithms. It adjusts the sleep/wake-up period of the node and CHs for transfer of packets to sink according to free slots. The algorithms working on the myopic state of channel presents the limiting condition and requires the increased time to predict the next state of the channel. The outcome of this contribution shows that the proposed scheduling algorithm reduces the number of conflicts in allocating the slots, this saves the energy, improves the network lifetime, and increases the throughput with minimum delay.

3. Synchronization Mechanism:

The aggregation and scheduling algorithms used for bandwidth utilizations requires the clock synchronization to improve the network performance. The slots of scheduling algorithm and clock of nodes are synchronized with a global time scale for communicating packets in specified time. It works on the formation of cluster-based spanning tree which synchronizes the nodes and sink level by level. The local clock of the node and the global clock of the network are synchronized to reduce the clock skew, synchronization errors and energy consumption. The research also proposes the hybrid synchronization mechanism where scheduling algorithm is used to allocate the conflict-free scheduling slots and synchronization algorithms are used to synchronize these slots to improve throughput. This contribution has five outcomes, Synchronized Data Aggregation (SDA) [46] algorithm- works on static node and sink. Bandwidth Efficient SDA (BESDA) [47] algorithm-with mobile nodes, Mobility–aware hybrid synchronization (MHS) [48] algorithm-Random mobility of nodes and Node Heterogeneity for Energy Efficient Hybrid Synchronization (NHES) [49] and Heterogeneity–aware Bandwidth Efficient Hybrid Synchronization for Wireless Sensor Network [50] algorithm-uses heterogeneous and mobile nodes in the network. The hybrid approach used helps to reduce clock drifts, synchronization errors, energy consumption, delay and increases the throughput as compared to existing algorithms.

1.7. PUBLICATIONS

The contributions have been or are in the process of being, validated through peer-review publication in journal and conference proceedings. The relevant publications are listed below:

A. Journal Publications:

1. **Dnyaneshwar Mantri**, Neeli R Prasad, and Ramjee Prasad, "**Two Tier Cluster-based Data Aggregation (TTCDA) in Wireless Sensor Network**," Springer Journal Wireless Personal Communications, vol.75, Issue 4, pp. 2589-2606, November 2013.DOI 10.1007/s11277-013-1489-x.

2. **Dnyaneshwar Mantri**, Neeli R Prasad, Ramjee Prasad, "**BECPA: Bandwidth Efficient Cluster-based Packet Aggregation in Wireless Sensor Network**," Springer Journal, TTPBL special issue of Wireless Personal Communication, vol.76, Issue 3, pp. 335-349, March 2014, DOI 10.1007/s11277-014-1709-z.

3. **Dnyaneshwar Mantri**, Neeli R Prasad, Ramjee Prasad, "**Bandwidth Efficient Heterogeneity aware Cluster-based Data Aggregation for Wireless Sensor Network**," Elsevier Journal of Computer and Electrical Engineering, vol 41, pp. 256–264, January 2015, DOI:10.1016/j.compeleceng. 2014.08.008.

4. **Dnyaneshwar S. Mantri**, Neeli Rashmi Prasad, and Ramjee Prasad, "**Mobility and Heterogeneity-Aware Cluster-based Data Aggregation for Wireless Sensor Network**," Springer Journal-Wireless Personal Communication, vol. 86, Issue 2, pp. 975-993, January 26, 2016, DOI:10.1007/s11277-015-2965-2.

5. **Dnyaneshwar S. Mantri**, Neeli Rashmi Prasad, and Ramjee Prasad, "**Heterogeneity–aware Bandwidth Efficient Hybrid Synchronization for Wireless Sensor Network**," 7th International Conference on Communication, Computing and Virtualization (ICCCV-16), Extended in International Journal of Computer Application (IJCA)- ISSN 0975–8887 (Accepted).

B. International conferences

1. **Dnyaneshwar Mantri**, Neeli R Prasad, Shingo Ohmori, and Ramjee Prasad, "**Two-Tier Cluster-based Data Aggregation (TTDCA) for Wireless Sensor Networks**," 6th IEEE International Conference on Advanced Networks and Telecommunication Systems (ANTS12), pp. 117-122, Dec 19-20, 2012, Bangalore, India.

2. **Dnyaneshwar Mantri**, Neeli R Prasad, and Ramjee Prasad, "**Grouping of Clusters for Efficient Data Aggregation (GCEDA) in Wireless Sensor Network**," 3rd IEEE International Advance Computing Conference (IACC-2013), pp. 132-137, Feb. 22-23, 2013, Ghaziabad, India.

3. **Dnyaneshwar Mantri**, Neeli R Prasad, and Ramjee Prasad, "**BECPA: Bandwidth Efficient Packet Aggregation for Wireless sensor network**," 2nd International Conference on Mobility for life: Technology, Telecommunication & Problem-based Learning (TTPBL-2013), pp. 87-91, March 14-16, 2013, Nashik, India.

4. **Dnyaneshwar Mantri**, Neeli R Prasad, Ramjee Prasad, "**MHBCDA: Mobility and Heterogeneity aware Bandwidth Efficient Cluster-based Data Aggregation for Wireless Sensor Network**," Wireless Vitae 2013, pp. 1-5, June 22-24, 2013, Atlanta City, New Jersey, USA.

5. **Dnyaneshwar Mantri**, Neeli R Prasad, Ramjee Prasad, "**BHCDA: Bandwidth Efficient Heterogeneity aware Cluster-based Data Aggregation for Wireless Sensor Network**," 2nd International Conference on Advances in Computing, Communications and Informatics (ICACCI2013), pp. 1065-1069, August 22-25, 2013. Mysore, India.

6. **Dnyaneshwar Mantri**, Pranav Pawar, Neeli R Prasad, and Ramjee Prasad, "**Cluster-based Myopic and Non-myopic Scheduling for Wireless Sensor**

Network," 2014 IEEE Students' Technology Symposium (TechSym), pp. 116,120, Feb. 28-March 2, 2014, IIT Kharagpur, India.

7. **Dnyaneshwar Mantri**, Pranav Pawar, Neeli R Prasad, and Ramjee Prasad, "**An Efficient Schedule based Data Aggregation using Node Mobility for Wireless Sensor Network**," Wireless Vitae 2014, pp. 1-5, May 1-14, 2014. Aalborg, Denmark.

8. **Dnyaneshwar Mantri**, Neeli R Prasad, and Ramjee Prasad, "**Scheduled Collision Avoidance in Wireless Sensor Network using ZigBee**," 3rd International Conference on Advances in Computing, Communications and Informatics (ICACCI2014), pp. 2129-2134, Sept. 25-27, 2014, Delhi, India.

9. **Dnyaneshwar Mantri**, Neeli R Prasad, and Ramjee Prasad, "**Synchronized Data Aggregation for Wireless Sensor Network**," 1st IEEE Global Conference on Wireless Computing and Networking, pp. 263-267, Dec. 22-24, 2014, SIT, Lonavala, India.

10. **Dnyaneshwar S. Mantri**, Neeli Rashmi Prasad, and Ramjee Prasad, "**Bandwidth Efficient Hybrid Synchronization for Wireless Sensor Network**," 4th International Conference on Advances in Computing, Communications and Informatics (ICACCI2014), pp. 2108-2113, August 10-13, 2014. Kochi, India.

11. **Dnyaneshwar S. Mantri**, Neeli Rashmi Prasad, and Ramjee Prasad, "**Mobility-aware Hybrid Synchronization for Wireless Sensor Network**," WPMC 2015, Hyderabad, India (Presented).

12. **Dnyaneshwar S. Mantri**, Neeli Rashmi Prasad, and Ramjee Prasad, "**Node Heterogeneity for Energy Efficient Synchronization for Wireless Sensor Network**," 7th International Conference on Communication, Computing and Virtualization (ICCCV-16), in association with Elsevier B.V. Amsterdam, Procedia Computer Science vol 79, pp. 885-892, Feb. 26-27, 2016, Mumbai, India.

1.8. THESIS OUTLINE

This section provides an outline of the thesis with a brief description of the individual chapters as shown in Figure 1-6 with individual chapter contributions.

Chapter 2: Data Aggregation Algorithms for Bandwidth Management in WSN

Chapter 2 introduces the concept of data aggregation mechanisms in WSNs, its requirement, aggregation issues, and challenges in framework design. It also gives an in-depth comparison of the tree and cluster-based data aggregation algorithms. The proposed cluster-based data aggregation algorithm works on two levels as intra and inter-cluster aggregation. The additive and divisible aggregation functions at CHs and sink removes the redundant data and shows improved performance [7]. The aggregation functions are applied according to the semantic (equal) and temporal (different) conditions of data and packets generated by the nodes at a variable rate. The chapter also discusses the energy model used in aggregation. The chapter also presents the algorithm based on grouping of nodes and CHs for reduced energy consumption and delay. The proposed algorithms show improvement in network lifetime, throughput with reduced energy consumption. The contribution of the chapter is published in A1: TTCDA [7], B1: TTCDA [35] and B2: GCEDA [36] according to publication list in section 1.7.

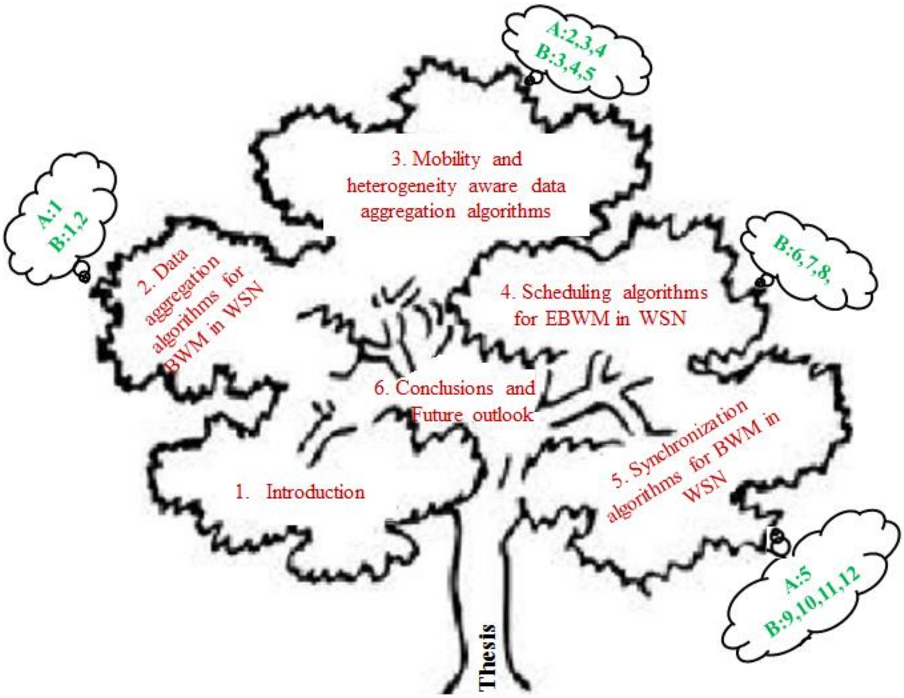


Figure 1- 6 Thesis organization and contributions

Chapter 3: Mobility and Heterogeneity-aware Data Aggregation Algorithms

Chapter 3 address the challenges in aggregating the information in the heterogeneous and mobile scenario of the network. To reduce the energy consumption and increase bandwidth utilization and lifetime, a network with heterogeneous nodes and the mobile sink is formed. The proposed aggregation algorithms consider the fixed region for aggregation of packets and data within the packet. The rate-based aggregation used, consider the correlation of packets and random data generated by nodes at a variable rate. The perfectly compressible aggregation function at CH and sink shows reduced energy consumption, communication cost, throughput and improved lifetime of the network. The contribution of this chapter is published in A2: BECPA [38], A3: BECDA [42], A4: MHCDA [40] and B3: BECPA [37], B4: MHBCDA [39], B5: BHCDA [41] according to publication list in section 1.7.

Chapter 4: Scheduling Algorithms for Efficient Bandwidth Utilization in WSN

Chapter-4, address the issues of scheduling and proposes the conflict-free scheduling mechanism for collision avoidance based on the static and mobile nodes and sink in the network. The proposed scheduling algorithms (CMNS [43], SDNM [44] and CMNMS) consider the hierarchical cluster-based mechanism and discuss the system model based on the myopic and non-myopic state of the channel. The proposed scheduling mechanism uses TDMA as basic MAC for allocating the conflict-free slots to reduce energy consumption, delay and increased throughput. The chapter also proposes Scheduled Collision Avoidance (SCA [45]) algorithm, which use hybrid approach of scheduling by combination of CSMA and TDMA technique to reduce the collisions, and shows improved performance as compared with existing. The contribution of this chapter is published in B6: CMNS [43], B7: SDNM [44] and B8: SCA [45] according to publication list in section 1.7.

Chapter 5: Synchronized Algorithms for Bandwidth Utilization in WSN

Chapter-5 illustrates the classification, comparison of synchronization mechanisms, and gives the requirements to develop the hybrid algorithm for an increase in throughput by synchronizing the slots. The cluster-based SPT mechanism is used to synchronize the nodes at lower level and sink. The level-by-level synchronization of nodes and sink reduces the possibility of errors and improves the throughput. The chapter also proposes the hybrid approach (scheduling and synchronization) of synchronization. The simulation results show that proposed algorithms lead to reduced errors, overheads, energy consumption and delay and enhances throughput as compared with existing. The effectiveness of the algorithm is arbitrated with static and mobile scenarios of node and sink. The contribution of this chapter is published in A5: HBES [50], and B9: SDA [46], B10: BESDA [47] and B11: MHS [48], B12: NHES [49] according to publication list in section 1.7.

Chapter 6: Conclusions and Future Outlook

The chapter provides the summary of the contribution and recommendations for the development of lightweight bandwidth management framework for WSNs. It also discusses the future research work.

1.9. REFERENCES

[1] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci,“Wireless sensor networks: a survey,”Journal of Computer Networks, 38(4), pp. 393–422, March 2002.

[2] Kazam Sharbey, Daniel Minoli, and Taieb Zanti, “Wireless Sensor Networks, Technology, Protocols and Applications,” Published by John Wiley & Sons, Inc., Hoboken, New Jersey, 2007.

[3] Fasolo E, Rossi M., Widmer J, and Zorzi M. “In-network aggregation techniques for wireless sensor networks: a survey,” IEEE Wireless Communications, 14(2), pp.70-87, April 2007.

[4] Krishnamachari B, Estrin D, and Wicker S, “The impact of data aggregation in wireless sensor networks,” 22nd International Conference on Distributed Computing Systems Workshops, pp. 575- 578, 2002.

[5] Mohamed Watfa, William Dahir, and Hishman Al Azar,“A sensor network Data Aggregation Technique,” International Journal of Computer Theory and Engineering, 1(1), pp. 1793-8201, April 2009.

[6] Ameer Ahmed Abbasi, and Mohamed Younis, “A survey on clustering algorithms for wireless sensor networks,” Computer Communications, vol 30, pp. 14-15, Oct. 2007.

[7] Dnyaneshwar Mantri, Neeli R Prasad, and Ramjee Prasad, “Two Tier Cluster-based Data Aggregation (TTCDA) in Wireless Sensor Network,” Springer Journal of Wireless Personal Communications, 75(4), pp. 2589-2606, Nov. 2013.

[8] Chitnis M, Pagano P, Lipari G, and Yao Liang, “A Survey on Bandwidth Resource Allocation and Scheduling in Wireless Sensor Networks,” International Conference onNetwork-Based Information Systems, 2009. NBIS '09. pp.121-128, Aug. 2009.

[9] Nastasi C, Marinoni M, Santinelli L, Pagano P, Lipari G, and Franchino G, “BACCARAT: a dynamic real-time bandwidth allocation policy for IEEE 802.15.4,” 8th IEEE International Conference on Pervasive Computing and Communications Workshops (PERCOM Workshops), pp. 406-412, April 2010.

[10] Ozlem Durmaz Incel, Lodewijk Van Hoesel, Pierre Jansen, and Paul Havinga, “Impact Of Network Density on Bandwidth Resource Management in WSN,” University of Twente Publications pp. 1-14, 2005.

[11] SeongHwan Cho, and Kee-Eung Kim, "Variable bandwidth allocation scheme for energy efficient wireless sensor network," 2005 IEEE International Conference onCommunications, 2005. (ICC 2005), vol.5, pp. 3314-3318, May 2005.

[12] Neeraj kumar, Manoj Kumar, and R B Patel, "Optimized Bandwidth Utilization for Real-Time Applications In Wireless Sensor Network," 2010 International Journal of Computer Applications (0975–8887), 1(6), pp. 92-97, 2010.

[13] Gerald Wagenknecht, Markus Anwander, and Torsten Braun, "MARWIS: A Management Architecture for Heterogeneous Wireless Sensor Networks," J. Harju et al. (Eds.): WWIC 2008, LNCS 5031, pp.177–188, 2008.

[14] Jamal N. Al-Karaki, Raza Ul-Mustafa, and Ahmed E. Kamal, "Data aggregation and routing in Wireless Sensor Networks: Optimal and heuristic algorithms," Computer Networks, 53(7), pp. 945-960, May 2009.

[15] Wen-Hwa Liao, Yucheng Kao, and Chien-Ming Fan, "Data aggregation in wireless sensor networks using ant colony algorithm," Journal of Network and Computer Applications, 31(4), pp. 387-401, Nov. 2008.

[16] Sudip Misra, P. Dias Thomasinous, "A simple, least-time, and energy-efficient routing protocol with one-level data aggregation for wireless sensor networks," The Journal of Systems and Software vol.83, pp. 852–860, 2010.

[17] Wenbo He, Xue Liu, and Klara Nahrstedt, "PDA: Privacy preserving data Aggregation for information Collection," ACM Transactions on Sensor Networks, 8(1), Article 6, pp. 1- 22, Aug. 2011.

[18] Huifang Chen, Hiroshi Mineno, and Tadanori Mizuno, "Adaptive data aggregation scheme in clustered wireless sensor networks," Computer Communications, 31(15), pp. 3579-3585, Sept. 2008.

[19] Sabrina Sicari, Luigi Alfredo Grieco, Gennaro Boggia, and Alberto Coen-Porisini, "DyDAP: A dynamic data aggregation scheme for privacy aware wireless sensor networks," Journal of Systems and Software, 85(1), pp. 152-166, Jan. 2012.

[20] Cheng Wang, Shaojie Tang, Xiang-Yang Li, and Changjun Jiang, "SelectCast: Scalable data aggregation scheme in wireless sensor networks," 2011 Proceedings of IEEE INFOCOM, pp. 296-300, April 2011.

[21] Chuan-Yu Cho, Chun-Lung Lin, Yu-Hung Hsiao, Jia-Shung Wang, and Kai-Chao Yang, "Data Aggregation with Spatially Correlated Grouping Technique

on Cluster-Based WSNs," 2010 Fourth International Conference onSensor Technologies and Applications (SENSORCOMM), pp. 584-589, July 2010.

[22] Hariharan S, and Shroff N.B, "Maximizing Aggregated Information in Sensor Networks Under Deadline Constraints," IEEE Transactions on Automatic Control, 56(10), pp. 2369-2380, Oct. 2011.

[23] Woo-Sung Jung, Keun-Woo Lim, Young-Bae Ko, and Sang-Joon Park, "A Hybrid Approach for Clustering-based Data Aggregation in Wireless Sensor Networks," 2009 Third International Conference on Digital Society, pp. 112-117, Feb.2009.

[24] Changhee Joo, Jin-Ghoo Choi, and Shroff N.B, "Delay Performance of Scheduling with Data Aggregation in Wireless Sensor Networks," 2010 Proceedings IEEEINFOCOM, pp. 1-9, March 2010.

[25] Shrikant B,Harish M, and Bhattacharjee R, "An Energy Efficient Hybrid MAC Protocol for WSN containing Mobile Nodes," International Conference on Information, Communication and Signal Processing (ICICS),pp.1-5, Dec 2011.

[26] Victor Cionca, Thomas Newe, and Vasile Dadarlat, "TDMA Protocol Requirements for Wireless Sensor Networks," The Second International Conference on Sensor Technologies and Applications, pp.30-35, 2008.

[27] Shihan Li, Depei Qian, Yi Liu, and Jie Tong, "Adaptive Distributed Randomized TDMA Scheduling For Clustered Wireless Sensor Networks," WiCOM, pp. 2688-2691, 2007.

[28] Stevan Marinkovic, Christian Spagnol, and Emanuel Popovici, "Energy-Efficient TDMA-based MAC Protocol for Wireless Body Area Networks," Third International Conference on Sensor Technologies and Applications, 2009 (SENSORCOMM '09), pp. 604-609, June 2009.

[29] WOO, A AND CULLER, D. A, "Transmission Control Scheme for Media Access in Sensor Networks," In Proceedings of the Seventh International ACM Conference on Mobile Computing and Networking (MOBICOM) pp.1-15, 2001.

[30] G. Gupta, M. Younis, "Load-Balanced Clustering in Wireless Sensor Networks," Proceedings of International Conference on Communications (ICC 2003), vol.3, pp. 1848-1852, May 2003.

[31] Rout R.R., Ghosh S.K., Chakrabarti S., "Network coding-aware data aggregation for a distributed Wireless Sensor Network," 2009 International Conference on Industrial and Information Systems (ICIIS) pp.32-36, Dec. 2009.

[32] Bharath Sundararaman, Ugo Buy, and Ajay D. Kshemkalyani., “Clock synchronization for wireless sensor networks: A survey,” Ad Hoc Networks Elsevier, 3:28, pp. 1–323, 2005.

[33] Saurabh Ganeriwal, Ram Kumar, and Mani B. Srivastava. Timing-sync protocol for sensor networks. In Proceedings of the 1st International Conference on Embedded Networked Sensor Systems, SenSys ’03, pp. 138–149, New York, NY, USA, 2003.

[34] Weilian Su and I.F. Akyildiz. Time-diffusion synchronization protocol for wireless sensor networks. Networking IEEE/ACM Transactions on, 13(2), pp. 384–397, April 2005.

[35] Dnyaneshwar Mantri, Neeli R Prasad, Shingo Ohmori, and Ramjee Prasad, “Two-Tier Cluster-based Data Aggregation (TTDCA) for Wireless Sensor Networks,” 6th IEEE International Conference on Advanced Networks and Telecommunication Systems (ANTS12), pp. 117-122, Dec. 2012.

[36] Dnyaneshwar Mantri, Neeli R Prasad, and Ramjee Prasad, “Grouping of Clusters for Efficient Data Aggregation (GCEDA) in Wireless Sensor Network,” 3rd IEEE International Advance Computing Conference (IACC-2013), pp. 132-137, Feb. 2013.

[37] Dnyaneshwar Mantri, Neeli R Prasad, and Ramjee Prasad, “BECPA: Bandwidth Efficient Packet Aggregation for Wireless sensor network,” 2nd International Conference on Mobility for life: Technology, Telecommunication & Problem-based Learning (TTPBL-2013), pp. 87-91, March 14-16, 2013, Nashik, India.

[38] DnyaneshwarMantri, Neeli R Prasad, Ramjee Prasad, “BECPA: Bandwidth Efficient Cluster-based Packet Aggregation in Wireless Sensor Network,” Springer Journal, TTPBL special issue of Wireless Personal Communication, 76(3), pp. 335-349, March 2014.

[39] Dnyaneshwar Mantri, Neeli R Prasad, Ramjee Prasad, “MHBCDA: Mobility and Heterogeneity aware Bandwidth Efficient Cluster-based Data Aggregation for Wireless Sensor Network,” Wireless Vitae 2013, pp. 1-5, June 2013.

[40] Dnyaneshwar Mantri, Neeli Rashmi Prasad, & Ramjee Prasad, “Mobility and Heterogeneity aware Cluster-Based Data Aggregation for Wireless Sensor Network,” Springer Journal of Wireless Personal Communication, 86(2), pp. 975-993, Jan. 2016.

[41] Dnyaneshwar Mantri, Neeli R Prasad, Ramjee Prasad, “BHCDA: Bandwidth Efficient Heterogeneity aware Cluster-based Data Aggregation for Wireless

Sensor Network," 2nd International Conference on Advances in Computing, Communications and Informatics (ICACCI2013), pp. 1065-1069, Aug.2013.

[42] Dnyaneshwar Mantri, Neeli R Prasad, Ramjee Prasad, "Bandwidth Efficient Heterogeneity aware Cluster-based Data Aggregation for Wireless Sensor Network," Elsevier Journal of Computer and Electrical Engineering, vol 41, pp. 256–264, Jan. 2015.

[43] Dnyaneshwar Mantri, Pranav Pawar, Neeli R Prasad, and Ramjee Prasad, "Cluster-based Myopic and Non-myopic Scheduling for Wireless Sensor Network," 2014 IEEE Students' Technology Symposium (TechSym), pp. 116-120, March 2014.

[44] Dnyaneshwar Mantri, Pranav Pawar, Neeli R Prasad, and Ramjee Prasad, "An Efficient Schedule based Data Aggregation using Node Mobility for Wireless Sensor Network," Wireless Vitae 2014, pp. 1-5, May 2014.

[45] Dnyaneshwar Mantri, Neeli R Prasad, and Ramjee Prasad, "Scheduled Collision Avoidance in Wireless Sensor Network using ZigBee," 3rdInternational Conference on Advances in Computing, Communications and Informatics (ICACCI2014), pp. 2129-2134, Sept. 2014.

[46] Dnyaneshwar Mantri, Neeli R Prasad, and Ramjee Prasad, "Synchronized Data Aggregation for Wireless Sensor Network," 1st IEEE Global Conference on Wireless Computing and Networking, pp. 263-267, Dec. 2014.

[47] Dnyaneshwar S. Mantri, Neeli Rashmi Prasad, and Ramjee Prasad, "Bandwidth Efficient Hybrid Synchronization for Wireless Sensor Network," 4th International Conference on Advances in Computing, Communications and Informatics (ICACCI2014), pp. 2108-2113 Aug. 2014.

[48] Dnyaneshwar S. Mantri, Neeli Rashmi Prasad, and Ramjee Prasad, "Mobility-aware Hybrid Synchronization for Wireless Sensor Network," WPMC 2015, Hyderabad, India (Presented).

[49] Dnyaneshwar S. Mantri, Neeli Rashmi Prasad, and Ramjee Prasad, "Node Heterogeneity for Energy Efficient Synchronization for Wireless Sensor Network," 7th International Conference on Communication, Computing and Virtualization (ICCCV-16), in association with Elsevier B.V. Amsterdam, Procedia Computer Science vol 79, pp. 885-892, Feb. 2016.

[50] Dnyaneshwar S. Mantri, Neeli Rashmi Prasad, and Ramjee Prasad, "Heterogeneity–aware Bandwidth Efficient Hybrid Synchronization for

Wireless Sensor Network," Extension of (ICCCV-16) in International Journal of Computer Application (IJCA)- ISSN 0975–8887 (Accepted).

CHAPTER 2. DATA AGGREGATION ALGORITHMS FOR BANDWIDTH MANAGEMENT IN WSN

Wireless Sensor Networks (WSNs) are used for Data collection, processing and transmission in the events of interest. In recent years, many techniques for data gathering are proposed based on the applications with a focus on performance metrics such as energy consumption, accuracy, delay, throughput, reliability, channel utilizations, lifetime, and so on. This chapter presents the in-depth survey of data aggregation algorithms and proposes the new approach for choosing an appropriate method. Firstly, the concept of data aggregation along with challenges in designing of data collection and aggregation methods are discussed. Subsequently, typical data aggregation mechanisms based on flat and cluster-based networks are presented. Particularly, the cluster-based approach is used to evaluate the performance of WSNs. The chapter has two contributions, Two-Tier Cluster-based Data Aggregation (TTCDA) [6-7] and Grouping of Clusters for Effective Data Aggregation (GCEDA) [8] algorithm. It proposes the new metric of CH election for aggregation of data. The proposed rate based aggregation uses the perfectly compressible aggregation functions at CH and sink to reduce the packet count hence reduced communication cost, energy consumption and improved throughput. It also proposes energy model used in aggregation and the method of grouping the clusters for reducing the energy consumption. The chapter analytically evaluates the proposed protocols for improvement of Quality of service (QoS) parameters. Finally, the chapter concludes by pointing out possible future research.

2.1. INTRODUCTION

In the growing era of WSN applications, the primary function of the node is to sense the event of interest used for measurement and control purpose from environment like temperature, humidity or pressure at an instant of time. The information collected is random with redundant data and needs to be processed before transmission to sink. The nodes used for collection are small and has limitation of resources as storage energy, and bandwidth. It restricts the processing and communication capabilities of the node in the network [1-7]. The data collected from nodes contains the redundant information, which consumes energy, communication bandwidth and increases the communication cost. It necessitates the need of strategy for data aggregation to improve the QoS parameters of the WSN networks. Depending on the volume and type of data the different mathematical functions like sum, count, min, max, avg, median, etc are used in the aggregation algorithms to reduce the redundancy and packet count reaching to sink [7]. The data aggregation algorithms aim to reduce the energy consumption, collision of packets, transmission cost and required communication bandwidth [6-7]. The factors that effects on the aggregation algorithms are; network topology, formation of cluster, election of CH, node deployment, mobility and traffic patterns, transmission media, link quality and aggregation methods [1-2].

The existing data/ packet aggregation algorithms are classified according to their functionality as in-network processing [2], predefined grid or region of aggregation [3], Data-centric or address-centric aggregation [3], Tree-based aggregation [4-5], Cluster-based aggregation [6-8]. All these algorithms are used in specific condition like in-network processing is suitable for static nodes, grid-based approach for data-centric rather than address centric to send critical events and not suitable for localized events, "*tree-based approach performs aggregation in route, it shows improvement in network lifetime but has node failure problem and adaptability to dynamic changes in network topology* [4-6]". Cluster-based aggregation is suitable for hierarchical and scalable networks [6]. The details of different aggregation mechanism are described in section 2.2 and 2.3.

WSNs have problem of scalability, delay, loss of packets, and energy consumption due to limited resources of the node. The chapter proposes the cluster-based network for improving the QoS parameters like energy consumption, transmission delay, communication cost, and increase in the bandwidth utilization for a number of packets received at the sink [6-7]]. In a cluster-based network of WSN, resource allocation primarily relates to the amount of bandwidth given to the CH as an aggregator or gateway between source nodes and sink. The important feature of the cluster-based model is that, network remains operational even if one cluster head (CH) fails in the route. It stabilizes the network with scalable changes in the network topology. The proposed cluster-based data aggregation algorithms use the perfectly compressible aggregation function aiming to improve the losses caused due to the collision, delays and from the waste of bandwidth. The aggregation function considers the two levels of operation as intra and inter-cluster aggregation and communication of packets to CH and sink saving energy. It improves the network lifetime and bandwidth utilization [6-7].

The chapter addresses the challenges in data aggregation and proposes the methods to save energy, transmission cost and improve network lifetime. The concept is analytically supported and validated by simulation. The chapter has three contributions. It proposes the basic data aggregations techniques supported by cluster-based algorithms as Two Tier Cluster-based Data Aggregation Algorithm for WSN (TTCDA) [6-7]. TTCDA considers the rate based aggregation on the packets and random data generated by nodes. The rate based aggregation at CH and sink reduces the redundant data while packet aggregation saves 3.13% energy than data aggregation [6-7].

The second contribution is Grouping of Clusters for Efficient Data Aggregations Algorithm for WSN (GCEDA) [8].GCEDA uses the same principle of aggregation as TTCDA but differs in the principle of operation. Also, the concept of grouping the nodes at intra- cluster and CHs at inter-cluster aggregation and communication (GCEDA) shows the reduced energy consumption by 14.94 %. But, if network diameter increases it is increased approximately by 1%. The cluster-based network are used in WSN for data aggregation which gives best results for a scalable network with minimum variations in topology and energy consumption as compared to the tree-based [6-8].

2.2. DATA AGGREGATION MECHANISMS

The main objective of data aggregation algorithm is to collect and process the sensed data from nodes for an increase in PDR and network lifetime by optimizing the resources of nodes (such as energy and bandwidth). While decreasing energy consumption and increase in bandwidth utilization, data aggregation algorithms may degrade the important QoS metrics in WSNs, such as data accuracy, latency, fault-tolerance, and security. Therefore, the design of an efficient data aggregation algorithm is an inherently challenging to find a trade-off between energy efficiency, data accuracy, and latency. The data aggregation techniques reduce the trade-off of energy and delay by properly routing the packets from node to sink. The structural variations in the network topology and method of aggregation is important in all the data aggregation algorithms. In many WSN protocols, aggregation and routing is efficiently done once at a time reducing the overheads [3, 6-7]. The data aggregation mechanism reduces the problem of congestion and improves the reliability of data collected by nodes surrounding the event. Figure 2-1 shows the different aggregation mechanisms used in the WSN along with the possibility of different types of nodes.

In-network Aggregation: Most of the aggregation algorithms use the fixed predefined grid or region for aggregation as in-network processing. The node with higher strength will be selected as an aggregator; this approach is suitable for static environment of network than dynamic [2, 7].

Grid-based Aggregation: It is highly suitable for mobile environments. An aggregator nodes is selected on the basis of geographical positions in the network in coordination with sink and grid center. The localized events need the critical information hence not suitable. [3, 6-7].

Tree-based Aggregation: In this data collected from leaf node is aggregated using data-centric protocols with distribution phase and a collection phase. In collection phases, data or packets are forwarded by the leaf node to sink through the respective parents. It increases the transmission delay hence require more energy. Also, node failure in the root blocks the data and has reduced packet delivery ratio [5-8].

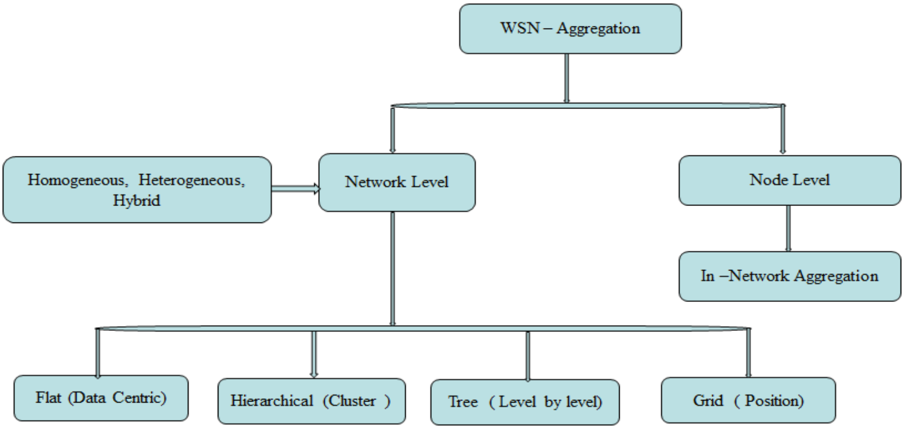


Figure 2- 1 Aggregation tree [9]

Table 2- 1 Comparison of data aggregation mechanisms

Aggregation	NWL	Throughput	Mob	RT	Hete	SC	Advantages	Disadvantage
In-Network [2]	increased	High	No	Less	No	No	Suitable for localized events, only critical information is passed to sink	Max time required in the decision of selecting Agg. node and uses fixed space.
Grid based [3]	Depend on time	High	Yes	Less	No	No	Adapts dynamic changes in topology suitable for mobile environment and reduces the traffic	Not suitable for localized events
Tree-based [5-6]	moderate	Less	No	High	No	No	Suitable for in-network aggregation	Failure of intermediate node causes topology change and causes much transmission delay
Cluster-based [10-12]	Extends	High	No	Less	No	No	It is more efficient and scalable	Formation of the cluster is difficult for the hetero node.

NWL- Network Lifetime, RT- Response time, Mob- Mobility, SC-Security, etc.

Cluster-Based Data Aggregation: It overcomes the problems of flat network specifically in the large-sized network. The data communication to sink from a node and CH uses the optimal path according to a number of hops used causing variation in the communication cost and reduction in the efficiency [6-8]. Instead of communicating information individually to sink data will be aggregated at CH and send it to sink. Many protocols using cluster-based approach for data aggregation are explored in [10-12, 14-15]. The cluster-based data aggregation improves scalability to network changes and reduces the energy consumption, improves bandwidth utilization with a lifetime of the network. The comparison between different Data aggregation mechanisms is shown in Table 2-1.

2.3. RELATED WORKS

It gives an in-depth idea about the methodology and mechanisms of data aggregation algorithms used in WSNs. It focuses on the tree and cluster-based approaches, which clearly differentiates the advantage of using cluster-based data aggregation over flat.

2.3.1. FLAT NETWORK-BASED AGGREGATION

One of the basic approach used in the flat network based aggregation is tree. It performs the aggregation in route and more susceptible to the failure of an intermediate node. It is also not adaptable to the dynamic changes in the network topology. In [4], data gathering tree is constructed for improving the network lifetime by use of nodes with heterogeneous and adjustable power level. The tree structure is adjusted according to the traffic flows from heavily loaded nodes in the route to transfer the data to its parent for finding upper bound of lifetime. It is suitable for low-density network having number of nodes less than 25 due to long computational time. In [5], another approach of improving the network lifetime and energy efficiency is proposed using spanning tree based algorithms. E-span selects the root to sink from leaf nodes based on highest available residual energy and distance.

Lifetime preserving tree (LPT) uses highest residual energy node as aggregating parent. It also has self-tree reconstruction feature when nodes are not functional and broken link is detected. However, it consumes more time in formation of tree and lifetime decreases. Ant Colony Algorithm (ACO) [13] finds the optimal way of aggregating and forwarding the data from source nodes to sink with reduced energy costs. The optimal low latency paths are selected according to opportunistic aggregation if same data is aggregated from the branches it is replaced by a single message. *"Energy wise opportunistic aggregation near the source is not optimal and reduces the packet count reaching to sink [7]"*.

In all flat networks are not scalable for WSNs with increased number of nodes since node failure in the route reduces PDR, increases energy consumption in finding the optimal path at the cost of bandwidth requirements.

2.3.2. CLUSTER-BASED AGGREGATION

The cluster-based network used in WSN is helpful for reducing the communication delay by multi-hop communication. These networks can adapt the dynamic changes in the network topology. The CH aggregates the data of packets from the nodes based on the type and performs required aggregation function (additive or divisible). Different algorithms used for the formation of cluster and data gathering are explored in [10-12]. These algorithms present the basis for CH election and formation of clusters for improving the QoS parameters in WSN. Some algorithms use pre-collected information, probabilities assigned to the node, the number of neighboring nodes and residual energy while electing the CHs. In Cluster-Wide Correlated Grouping (CWCG) [14], the energy consumption is reduced by grouping the nodes in the cluster based on the spatial and temporal correlations among each other. One node will be elected as an aggregator (leader) and transfer the data to sink. The correlation strategy used by hybrid architecture (Static tree for routing and dynamic clustering) for suppression of data reduces transmission cost but increases the latency. In Adaptive Data Aggregation (ADA) [15], sink is responsible for deciding the reliability of featured event based on the reporting frequency of data from the network. It adjusts the degree of temporal aggregation at node, based on data reporting frequency while spatial aggregation degree is controlled by aggregation ratio at CH. The architectural variations are not scalable for dense WSN.

In [16], hybrid approach of (static and dynamic) clustering helps to improve energy efficiency. It adaptively switches the mode of clustering for aggregation of data based on the network dynamic. The main drawback is the switching delay and depends on the velocity of target used for the aggregation. Select Cast [17], explores combination of the single and multi-hop length aggregation schemes to achieve an optimal trade-off between aggregation throughput and gathering efficiency. The multi-hop length scheme is suitable for the perfectly compressible aggregation functions like mean and max applied on the semantic data received from nodes. Cluster-based and Tree-based Power Efficient Data Collection and Aggregation Protocol (CTPEDCA) [18] is designed to obtain the increased energy efficiency at reduced time complexity in the fully distributed hierarchical WSN. The performance metrics are achieved by using single CH as gateway for transmission of aggregated data using minimum spanning tree (MST) routing mechanism. Privacy–Preserving Data Aggregation (PDA) [19], presents two schemes (Cluster-*based Private Data Aggregation*-CPDA and Slice-*Mix-AggRegaTe*- SMART) using additive aggregation function solving the problem of collaborative data collection and data privacy. The performance of protocol is evaluated by aggregation data accuracy and reduced overloads.

Data merge [20], consider the data aggregation mechanisms without size reduction for achieving good accuracy. It considers the impact of different data flow scenarios such as traffic load and wait time interval. It is useful when overlapping paths exist in routing the packets causing delays in packet transfer.

In summary, the cluster-based protocol used for data aggregation has the trade-off of energy efficiency, delay and throughput, but scalable to the changes in the network dynamics. WSN with cluster-based aggregation is preferred over flat network based aggregation.

2.3.3. CLUSTER-BASED DATA AGGREGATION MODEL FOR WSN- A USE CASE

The data aggregation algorithms using cluster-based approach is suitable for static networks and need to be enhanced for dynamic variation. The important performance measurement parameters are the network lifetime and energy consumption and data transmission ratios. To mitigate the problems due to scarce network parameters of WSN, aggregation at CH and sink is proposed, which reduces the repetitive packets reaching to sink [6-7]. The data aggregation protocols based on hierarchical networks has more advantages than flat networks, few of them are listed here

1. Reduced overhead in cluster formation as compared to flat.
2. The network remains operational even if, one CH fails.
3. Lower latency due to short-range transmissions to the CH.
4. Has simple routing structure.
5. Improved scalability to dynamic changes in the network structure.

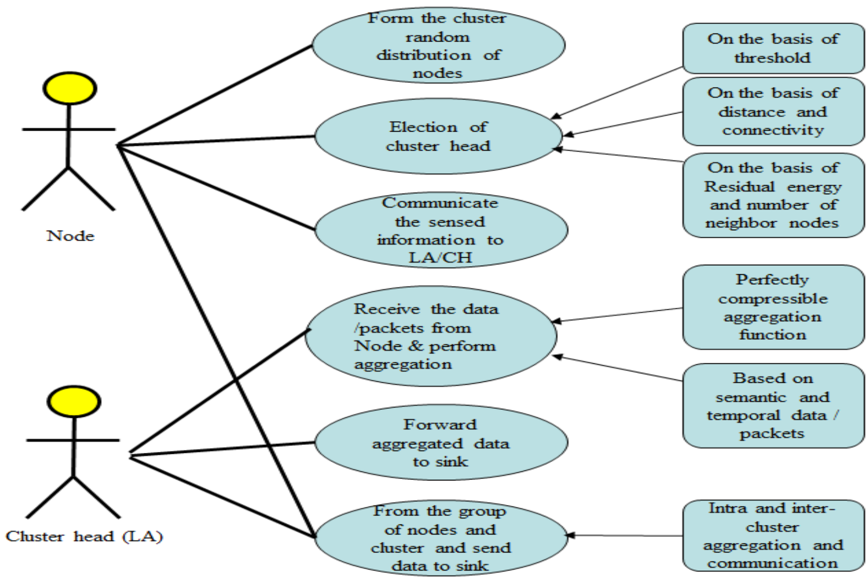


Figure 2- 2 Data aggregation model for WSN- a use case

In the static condition of the network, the control messages required for CH election causes overhead. In dynamic clustering mechanism only necessary nodes will participate in data aggregation, hence saves energy and sustains network for a long time. The model for data aggregation and the election of CH in the cluster-based network is shown in Figure 2-2. It gives the idea about the role of each node and local aggregator in the network.

2.4. TWO TIER CLUSTER-BASED DATA AGGREGATION ALGORITHM FOR WSN: TTCDA

Two Tier Cluster-based Data Aggregation Algorithm (TTCDA) [6-7] effectively reduce the energy consumption and improve bandwidth utilization in the transmission of packets generated at a variable rate. It uses the perfectly compressible aggregation function at intra and inter-cluster stage of aggregation reducing transmission cost. Also, CH and Sink takes into consideration the semantic and temporal correlation of packets for aggregation [6-7].

2.4.1. NODE AND NETWORK ASSUMPTIONS

This section gives the basic assumptions of node and network to obtain the results of TTCDA [7] and GCEDA [8]. All the nodes are static and homogeneous in terms of energy. These node generates data and packets at a variable rate independently. Each node in the pre-elected cluster had an identification number and synchronized with CH. The network is divided into numbers of clusters; every cluster has a CH and cluster members located at one hop. There are mixed links, unidirectional for intra-cluster and bidirectional for the inter-cluster aggregation [6-8].

2.4.2. NETWORK MODEL

"*The network is modeled as the connecting graph G(V, E) where nodes are represented by a set of vertices 'V' and wireless connecting edges 'E'[6]. If 'V' nodes* $\{S_1, S_2 \ldots S_V\}$ *in the network are randomly distributed and organized into 'n' clusters using a clustering algorithm[10], and then graph G is represented as G =* $\{C_1, C_2, C_3 \text{---} C_n\}$ *[6-7]. Now consider that each cluster has 'N' nodes out of which 'u' nodes '∀ u Є N' sense the event of interest in the specified time interval. Depending on sensing range nodes generates the variable set of data and packets* $\{r_1(t), r_2(t) \ldots r_u(t)\}$ *of fixed size. The CH performs aggregation* $f(A) = \{f(S_1), f(S_2), f(S_3) \ldots f(Su)\}$ *[6-7]*". The additive aggregation function at CH is defined by eq.(2-1) as,

$$f(A) = \sum_{i=1}^{u,} r_i(t) \qquad (2\text{-}1)$$

eq. (2-1) is applied on the data packets generated at a variable rate by consideration of semantic and temporal correlation. The network model used by TTCDA is shown in Figure 2-3.

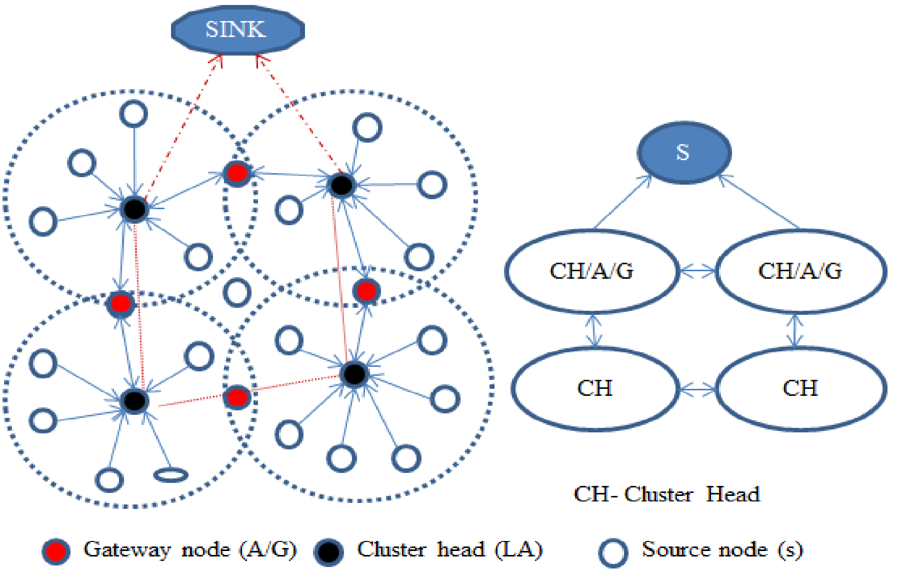


Figure 2- 3 Network model –TTCDA [6-7]

The network model consists of set of source (S) generating packets at a variable rate. "*Local Aggregator (LA) performs the intra-cluster aggregation of packets and data. Aggregator/Gateway (A/G) nodes forward the aggregated data packets from one cluster to other and to sink using uni and bi-directional links as one hop or multi-hop. It is assumed that S, LA, and A/G may change over the time* [6-7] ."

The proposed TTCDA for aggregation of data packets works on two levels as intra, and inter-cluster aggregation to reduce the packet count, transmission cost, and energy consumption with the minimum use of channel bandwidth [7].

2.4.3. AGGREGATION FUNCTIONS

"If X_i and Y_j are two variables representing the temporal and spatial correlation between a number of packets generated by the 'u' participating nodes in the cluster [7]." Let $i = 1... K$ nodes generate different number of packets and $j=1.... M$, nodes generate an equal number of packets, then the aggregation function defined in [6-7] are used to obtain the results.

1. *The sum function*: "*If each source node has variable PGR then the final aggregation value will be sum of packets from all participating nodes* [6-7]."

$$Sum = f(A_s) = \sum_{i=1}^{K}(X_i) \quad for\ \forall(X_i) = different\ PGR \tag{2-2}$$

2. *The Average function*: "*If data PGR of all source nodes is same, then the spatial correlation between them aggregates the packets/data as average* [6-7]."

$$Average = f(A_v) = \sum_{j=1}^{M}(Y_j) \quad for\ \forall\left(Y_j\right) = equal\ PGR \tag{2-3}$$

The redundant data is reduced to overcome the overheads in the communication of packets by selecting appropriate aggregation functions.

2.4.4. TTCDA ALGORITHM

"*The TTCDA algorithm operates in three phases (cluster formation, intra-cluster aggregation, and inter-cluster aggregation) as shown in Figure 2-4. In the initial phase randomly distributed nodes are organized into a number of clusters. A node clustering algorithm [11] is used for the formation of the cluster. The CH is elected according to highest residual energy, the minimum distance to sink and the highest number of neighbor nodes close together with one-hop connectivity [6, 12, 18], with above consideration the threshold for the node to become CH is revised in [7] and is given by eq. (2-4) as:*

$$T(n) = \frac{1}{1 - p(r \bmod 1/p)} \frac{E_r}{E_i} \frac{D_i}{D_{avg}} d_v \tag{2-4}$$

Where 'p' is the percentage probability of selecting CH, 'r' is the current round, (r mod (1/p)) is the representation of elected CHs. E_r is the residual energy after each round, and E_i is the initial energy. D_i is the degree of connectivity and D_{avg} is connectivity of the network. 'd_v' is the density of node within the selected range of cluster before the election of CH. Residual energy, the density of node and connectivity decides the election of the CH."

After the election of CH, data packets of fix size generated at variable rate are aggregated by CH [6]. The CH takes into account the correlation of packets generated by nodes to perform aggregation. CH performs divisible aggregation for same data/packets and additive aggregation on different data/ packets from nodes as intra-cluster aggregation and repeated in inter-cluster aggregation [7], where each CH acts as one node. Sink aggregates packets in the network.

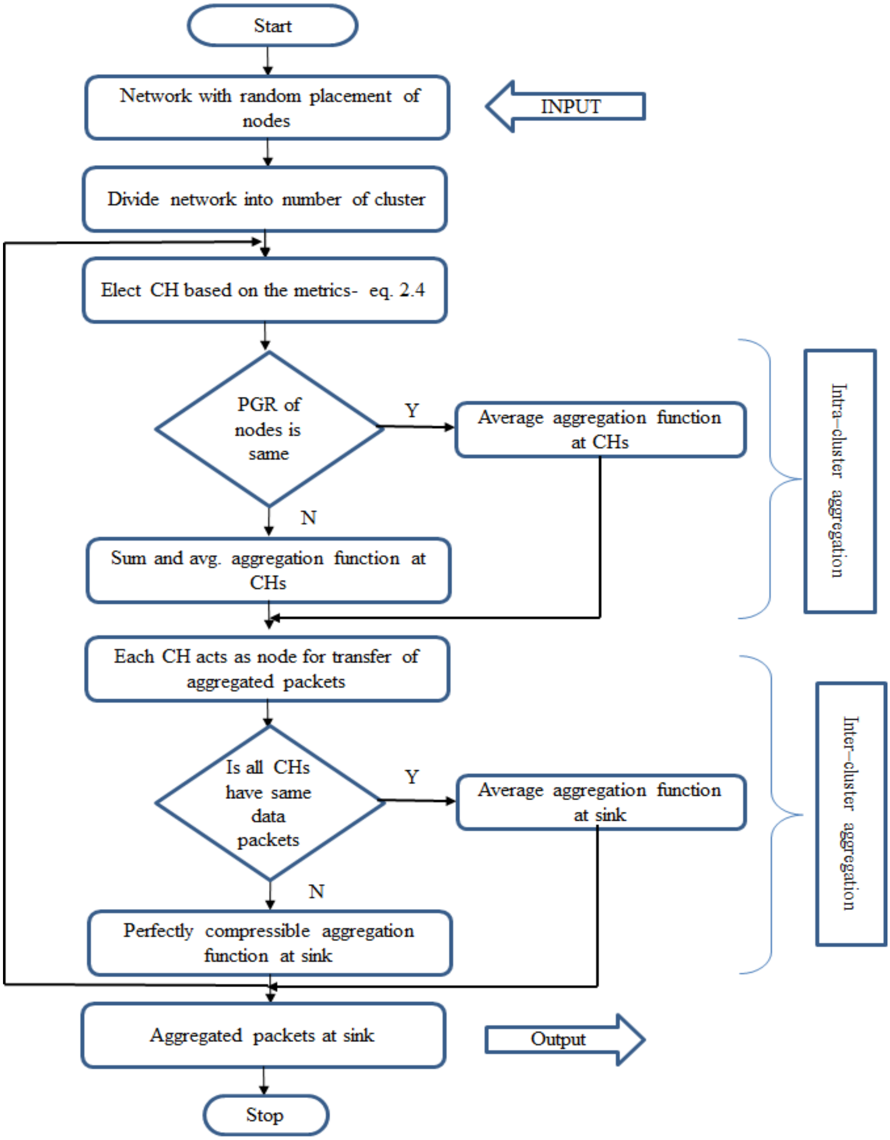


Figure 2- 4 Flow of TTCDA [7]

Intra-Cluster Aggregation:

Assume that, number of nodes 'N' are randomly distributed and aligned into respective clusters, after election of CH , the intra-cluster aggregation stage collects the information and process according to the eq. 2-2, and 2-3. The algorithm1 is used in intra-cluster phase to aggregate the packets generated by source nodes.

Algorithm1:Intra-cluster aggregation : Reduce the redundant data packets generated by source nodes at avariable rate[7]

Input: Graph *G (V, E)* with *'n'* clusters $G = \{C_1, C_2, C_3, \text{- -}\ C_n\}$, 'N' = source nodes in the clusterwith 'V' vertices, N Є *V*.
Output: CH with aggregated packets and data

Begin

Step1: for each cluster C_i *Є G*

Step2: if PGR of each node is same i.e. $\Pr_1 = \Pr_2 = ... = \Pr_u$

// $\Pr_u$ - packets generated by each participating node

then

Step3: $\text{Average of packets } A_v = \dfrac{\lfloor \Pr_1 + \Pr_2 + ... + \Pr_u \rfloor}{n_{us}}$

else

Step4: if PGR of each node is different i.e. $\Pr_1 \neq \Pr_2 \neq ...... \neq \Pr_u$

then

Step5: $\text{Sum of Packets } A_s = [\Pr_1 + \Pr_2 + ... + \Pr_u]$

else

Step6: if PGR is same for some nodes 'n_{us}' and different for some nodes 'n_{ud}

i.e. $(\Pr_1 = \Pr_2 = \Pr_6 = \Pr_{u-1}) \neq \Pr_3 \neq \Pr_{u-2} \neq \Pr_u$

then

Step7:

$$\textit{Network wide aggrgeation } A = A_v + A_s = \frac{\lfloor \Pr_1 + \Pr_2 + \Pr_6 + \Pr_{u-1} \rfloor}{n_{us}} + [\Pr_3 + \Pr_{u-2} + \Pr_u]$$

end if

end for

Step 8: end begin

Inter-cluster Aggregation:

"*In inter-cluster aggregation, each CH acts as a participating node. Considering graph G (V_C, Ec) with 'n' CHs, G = {CH_1, CH_2, CH_3 --- CH_n} of a graph G (V_c, E_c) with all V_C Є {all CH, Sink} and Ec are the edges connecting to all CHs and sink as input. The algorithm1 used for the intra-cluster aggregation operates recursively for the inter-cluster aggregation and communication with same assumptions [6-7].*"

2.4.5. ANALYTICAL DESCRIPTION OF ALGORITHM

Property 1: The Execution of TTCDA [6-7] algorithm produces a reduced number of information packets at CH using additive and divisible aggregation functions (intra-cluster ggregation).

"***Observation:*** *Consider network has 'V' nodes distributed in 'n' clusters. Each cluster has 'N' nodes with 'K' and 'M' participating nodes with different and same packets generating capacity respectively. The CH aggregates all the packets under three conditions[6-7].*

Example-1: *Assume that V=12, n=3, therefore G= {C_1, C_2, C_3} = {N_1-4, N_2-4, N_3-4} and the packets generated by nodes in cluster are C_1 (6, 6, 6, 6), C_2 (1, 6, 2, 7), C_3 (4, 4, 2, 2), Figure 2-5 shows the calculations for additive and divisible aggregation functions at CH and Table 2-2 gives the summary of theoretical calculations [6-7].*

Case-1: If PGR of nodes is at ER (C_1)

Number of packets without aggregation $= (r_1+r_2+ r_3 +r_4) = 24$

Number of packets with aggregation $= (r_1+r_2+ r_3+r_4) /4 = 06$

Case-2: If PGR of nodes is at DR (C_2)

Number of packets without aggregation $= (r_5+ r_6 +r_7 +r_8) = 16$

Number of packets with aggregation $= (r_5+ r_6 +r_7 + r_8) = 16$

Case-3: If PGR of some nodes is at ER and DR (C_3)

Number of packets without aggregation $= (r_9+ r_{10} + r_{11}+r_{12}) = 12$

Number of packets with aggregation $=(r_9+r_{10})/2+(r_{11}+r_{12}) /2 = 06$

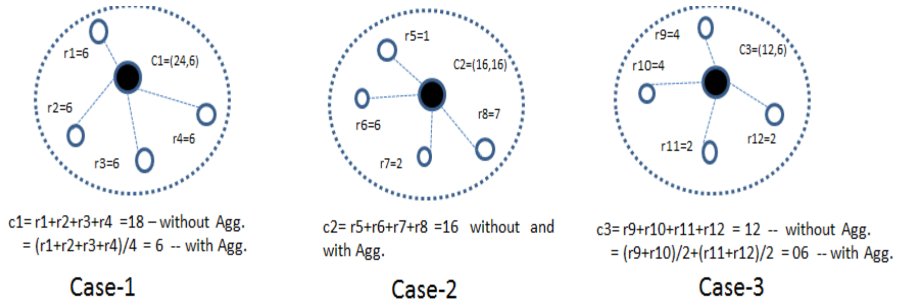


Figure 2- 5 Validation of TTCDA [7]

Table 2- 2 Summary of theoretical analysis [6-7]

Condition	**Case-1** **K=0, M= 4** Same PGR	**Case-2** **K=4, M=0** Different PGR	**Case-3** **K=2, M= 2** Same and diff. PGR	**Total packets at sink**
Without aggregation	24	16	12	52
With aggregation	06	16	06	28

Property 2: The execution of TTCDA [7] algorithm produces the reduced number of packets at a sink with inter-cluster aggregation.

Observation: Consider network has 'n' clusters. Each CH acts as participating node and transfers the aggregated 'k' packets for the second level of aggregation. The second level performs network-wide aggregation by forming tree structure as shown in Figure 2-6.

The CH performs the role of an aggregator or simply gateway to communicate the aggregated packets to sink for further processing. With intra-cluster aggregation number of clusters are n=3, therefore G = {ch_1, ch_2, ch_3} with {k_1-6, k_2-16, k_3-6}, the number of aggregated packets at each CH are ch_1 (6), ch_2 (16), ch_3 (6) then according to aggregation functions used in [6-7], the number of packets are calculated as,

Number of packets without aggregation (inter-cluster) = $Ch_1 + Ch_2 + Ch_3$ = 28

Number of packets with aggregation (inter-cluster) = 22

Total number of packets at sink without aggregation (network wide) = 52"

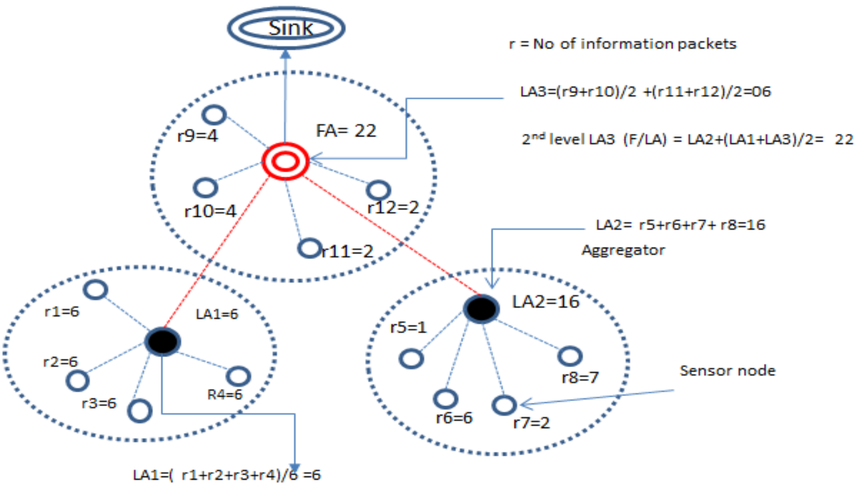


Figure 2- 6 Inter-cluster aggregation of TTCDA [7]

2.4.6. SIMULATION DETAILS

The proposed TTCDA [6-7] uses rate-based aggregation and the performance is compared with tree –based aggregation[4]. Table 2-3. gives the parameters used for node according to the trans-receiver model TR1000 [22-23].

Table 2- 3 Simulation parameters [6-7]

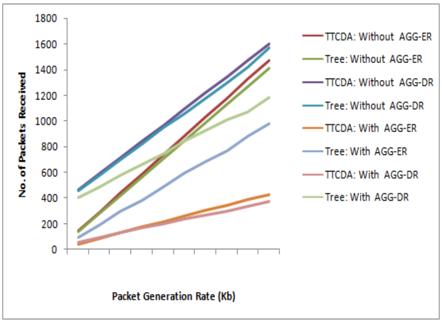
Parameter	Value
Network size	100 x 100 meters
Number of nodes	100
Placement of node	Random
Initial energy	100 J
Packet size	64 bytes
Ideal power	14.4mW
Transmission power	14.88mW
Receiving power	12.5mW
Simulation time	500 sec
Traffic model	Variable bit rate
Packet Generation Rate (PGR)	0.02-0.2 kb

2.4.7. RESULTS AND DISCUSSIONS

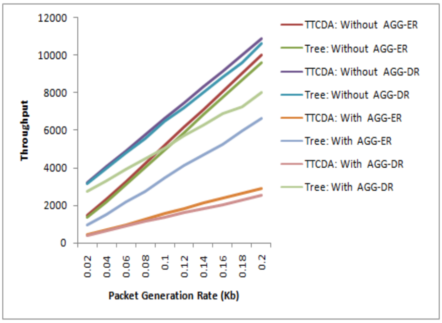
Results for TTCDA [6-7] are obtained by considering the number of packets that are generated at a variable rate from the nodes. The performance of TTCDA is compared with the tree-based network with and without aggregation.

Packet received by Sink: The performance of TTCDA is analysed on the basis of number of packets received by the sink. When the packet generation rate of each node (ER and DR) is varied from 0.02 to 0.2 kb/s, the number of packets reached to sink in TTCDA are increased by 4.25% and 2.94% as compared to tree-based approach without aggregation. With the application of aggregation function packets reached to sink drastically reduces by 55.25% and 72.47% in ER and DR as shown in Figure 2-7(a). The reduced packet count requires less bandwidth for the communication of packets to sink.

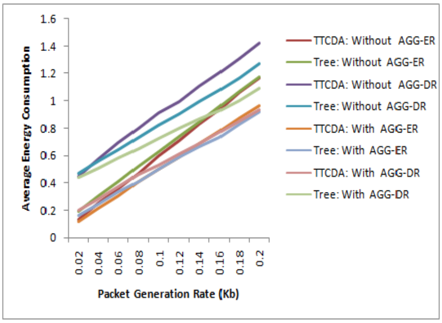
Throughput: It totally depends on how many packets are aggregated and reached to sink from source nodes. The throughput of TTCDA decrease from 19.18% (without aggregation) to 13.09% (with aggregation) at different PGR as compared with equal PGR as shown in Figure 2-7(b), which itself indicates that with aggregation TTDCA consumes less bandwidth [7]. The repetitive data packets from the nodes are dropped during aggregation causing less packets at sink (refer Table 2-4).



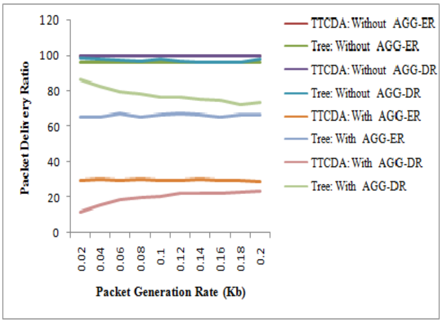
(a) Packets received by sink



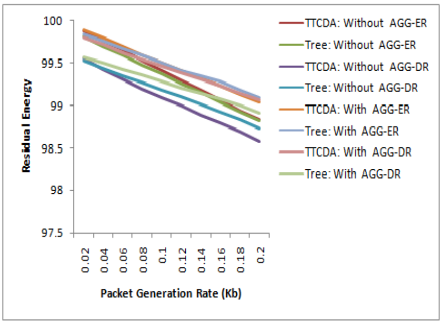
(b) Comparison of throughput



(c) Average energy consumption



(d) Packet delivery ratio



(e) Residual energy

Figure 2- 7 Results with varying PGR for TTCDA [6-7]

Average Energy Consumption: It depends on the packet rate received by the sink. According to the Figure 2-7(c), in different packet rate generation, energy consumption increases by 9.58%, however, it is reduced by 5.68% in equal rate as compared to State-of–the-art approach without aggregation. With aggregation the energy consumption is reduced by 24.83% as compared to tree. Due to random packet generation in DR, energy consumption is increased as compared to ER

Packet Delivery Ratio: From Figure 2-7(d) the PDR of TTCDA is increased by 4.25% and 2.75% without aggregation as compared to tree in ER and DR. With the application of appropriate (additive and divisible) aggregation, it is reduced by 54.96% and 74.38% respectively. In TTCDA, with aggregation the effective packet count reached to since is less, represents that TTDCA is bandwidth efficient than a tree [7].

Residual Energy: It is the remaining energy in the network. It indicates that how long the network can sustain for utilization of resources. The residual energy of TTCDA is more (1.13%) after each round of aggregation as compared to tree. By the consideration of diverse packet generation, the residual energy without aggregation is 0.74% less and 0.32% more with aggregation. TTCDA algorithm saves more energy in equal PGR as compared to DR.

Table 2-4 summarizes the results of TTCDA [7] with data and Packet aggregation. It is seen that data aggregation is prominent than packet aggregation.

Table 2- 4 Comparative results of packet and data aggregation – TTCDA [7]

Parameters	**TTCDA**			
	Packet aggregation		Data aggregation	
	ER	DR	ER	DR
No. of packets received	240	217	476	678
Throughput (%)	1684	1479	3326	4617
Avg. energy consumption (J)	0.54	0.57	0.51	0.66
PDR	29.77	19.98	55.48	65.84

2.5. GROUPING OF CLUSTERS FOR EFFICIENT DATA AGGREGATION: GCEDA

This section gives the new approach of aggregation by grouping the nodes in the cluster, generating the same data as intra-cluster aggregation. In the second stage of aggregation, CHs are grouped according to the number of packets [8, 14]. The CH decides the correlation of data packets, which are at one hop distance [8]. The proposed method of grouping the nodes and CH improves the energy consumption in the network with reduced delay [8].

2.5.1. PROPOSED NETWORK MODEL

"*The proposed network model of GCEDA [8] is as shown in Figure 2-8. It consists of a set of 'N' nodes {S_1, S_2 ... S_N} organized into 'n' clusters using a clustering algorithm [8, 10-11]"*. The number of nodes in each cluster are 'N/n' and are uniformly distributed. The nodes sense the event of interest and generate the packets at a variable rate according to eq. (2-1) in the specified time interval. In the first phase of the algorithm, the nodes in the cluster are grouped according to the packet generating capacity and represents the group as G = {G_1, G_2, G_3, --- G_n}. CH performs aggregation according to the eq. (2-2) and (2-3). In the second phase, CHs are grouped according to one hop communication and number of aggregated packets to form connected graph G_{CH} = {CH_1, CH_2, CH_3, --- CH_n} [8].

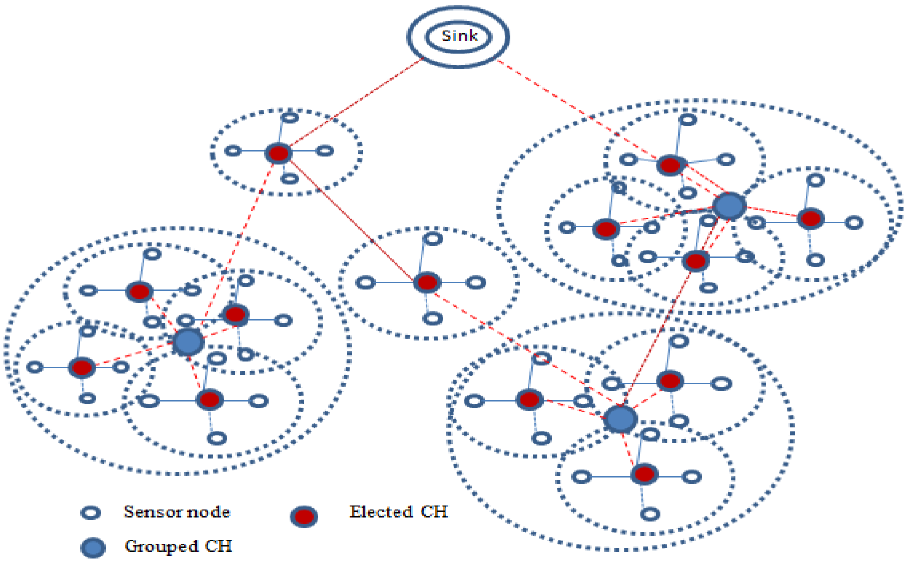


Figure 2- 8 Network model – GCEDA [8]

The basic design objectives of GCEDA [8] is to reduce the energy consumption by grouping the nodes of similar packet transferring capacity and then CH to transfer data packets to sink.

In the intra-cluster aggregation nodes are grouped according to PGR and CH performs the perfectly compressible aggregation function. In the second stage, grouping of CH is performed according to aggregated packets and CH close to sink transfers the aggerated packets.

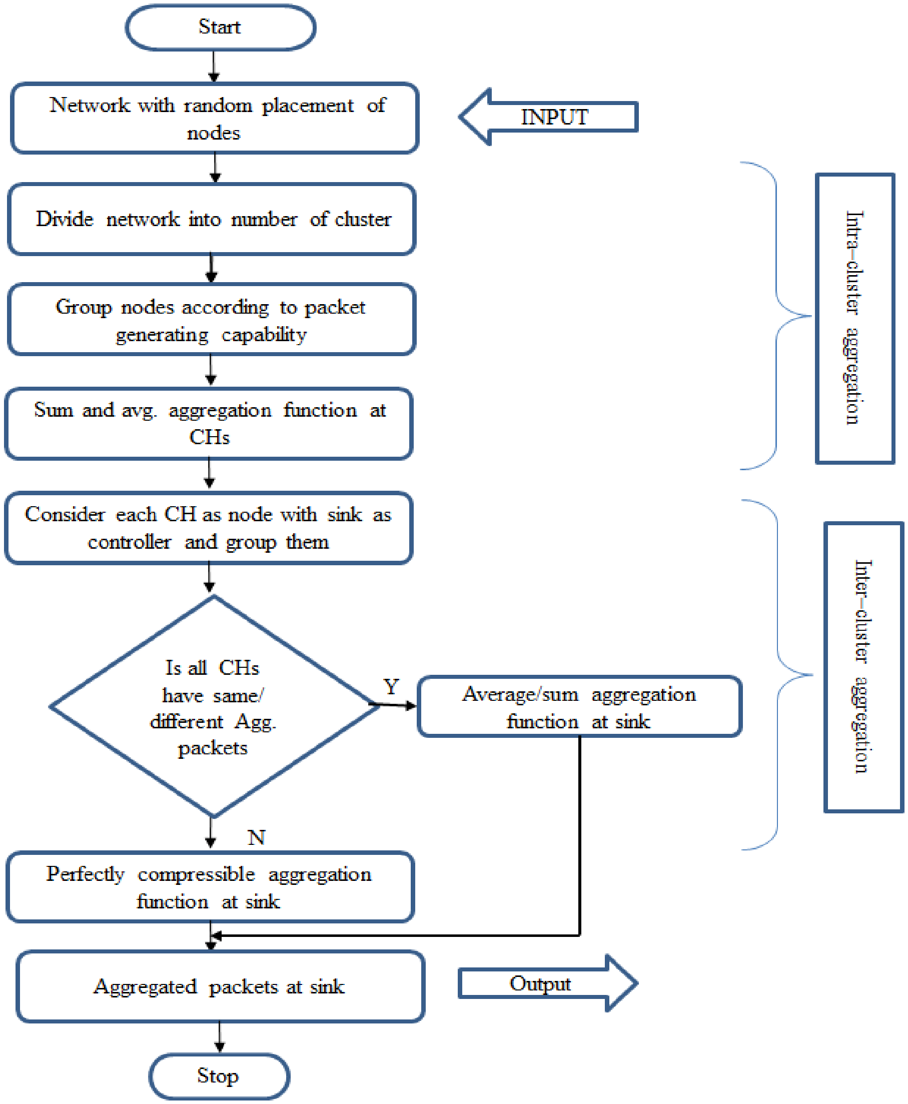


Figure 2- 9 Flow of GCEDA [8]

2.5.2. GCEDA ALGORITHM

The flow of GCEDA [8] algorithm for energy efficient communication of packets to sink is shown in 2-9. To work with GCEDA algorithm the uniformly distributed node organizes into the number of clusters (n) [8]. It elects CH according eq. (2-4) [7]. In the second phase, nodes having similar packet generation rate are grouped in the clusters for intra-cluster aggregation while CHs are grouped in an inter-cluster aggregation. The groups are rearranged periodically by sending the broadcast message. The use of perfectly compressible aggregation function, Grouping of nodes in intra-cluster and grouping of CH at inter-cluster reduces the number of packets reaching to the sink. With energy saving and prolong the network lifetime [8].

2.5.3. ENERGY DISSIPATION MODEL

Figure 2-10 shows the first order communication and energy model [24] extended and modified according to the requirements of GCEDA [8] It is the combination of trans-receiver electronics with the amplifier circuit.

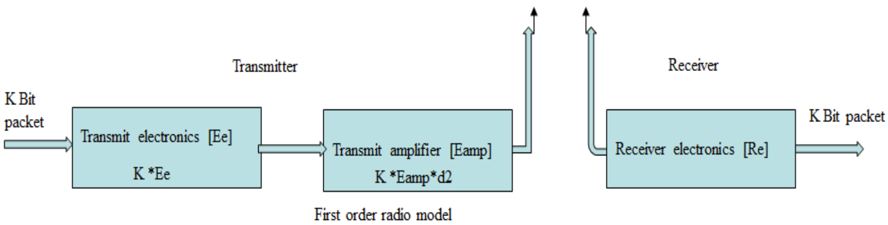


Figure 2-10 Energy dissipation model [8, 24]

Consider the network with ‘N’ nodes uniformly distributed in ‘n’ clusters, then the energy required to transfer 'K' bit of data packet to the CH and sink depends on the distance of the node from CH (d^2) and sink (d^4). eq. 2-5 represents the calculation of energy required according to [8, 24], is

$$ET_c = K * E_e + \begin{cases} K{*}E_S d^2 & d \le d_0 \\ K{*}E_l d^4 & d \ge d_0 \end{cases} \qquad (2\text{-}5)$$

where ‘E_s’= Energy required for node to transfer packet to CH, ‘E_l’ =Energy for CH to sink, ‘E_e’= Energy used by transmitter and receiver circuitry, ‘K’= Number of bits[8, 24]. The threshold distance ‘d_0’ is a function of amplifier energy required to transfer aggregated packets from node to sink and is given by eq. (2-6),

$$d_0 = \sqrt{E_S / E_l} \qquad (2\text{-}6)$$

The total energy consumed to receive K-bit message includes the cost of aggregation‘E_{DA}’ and trans-receiver electronics [8]. Most of the energy is dissipated in transmit/receive circuitry and amplifier in sending a signal of one bit.

$$ER_c = K{*}(E_e + E_{DA}) \qquad (2\text{-}7)$$

The number of nodes in each cluster under the uniform distribution are'N/n' and consumes energy CH (E_{ch}) given by eq.(2-8),

$$E_{ch} = K^* (E_e + E_S d^2) + (((N/n)-1) *K^*(E_e + E_{DA})) \tag{2-8}$$

The first part of eq. (2-8) indicates energy utilized by CH in broadcasting the message to form the group of similar nodes to transfer the packets within the cluster. *"The second part indicates the energy consumed in the reception of a message from {(N/n)-1} nodes in the cluster then eq. (2-8) can be rewritten* [8]" as

$$E_{ch} = K^* E_e (N/n) + K^* E_S d^2 + ((N/n)-1)^* K^* E_{DA}) \tag{2-9}$$

Data Transfer to Sink

The data transfer to sink takes place in two phases. In the initial phase, a similar group of nodes sends the data packets to CH where they are aggregated and packed into the frame. In the second phase, all CH are grouped and a number of groups is represented as 'm'. The CH from group at a one-hop distance to sink with highest residual energy transfers the aggregated packets to sink. Therefore, energy consumed by CH in data transmission per frame (E_{chF}) to sink is given by eq.(2-10) according to [8]

$$E_{chF} = K^* (E_e + E_l\, d^4) + [((N/n)-m+1)^* K^*(E_e + E_{DA})]$$

$$E_{chF} = K^* E_l\, d^4 + K^* E_e ((N/n)-m+2) + K^* E_{DA} ((N/n)-m+1) \tag{2-10}$$

The energy consumption in transmision of N_f /n data frames transmitted by each CH in one iteration is given by eq.(2-11) [8]. N_f= data frames from each iteration.

$$E_{chD} = N_f * F_1 * E_{chf} \qquad \text{where } F_1 = (1/K)\ ((N/n)-m+2) \tag{2-11}$$

Now according to various rounds, the energy consumption [8, 22] is

$$E_{Round} = (E_{ch/it})/m = (E_{ch} + E_{chD})/m \tag{2-12}$$

The another factor for consuming energy is the size of the network and active nodes in each cluster. With a constant area of the network, the size of the cluster depends on the optimum number of nodes in each cluster [8, 24, 25]. The maximum number of optimal CHs with network diameter 'M' is obtained using eq. (2-13),

$$n_{opt} = \sqrt{\frac{N}{2\Pi}} \sqrt{\frac{E_S}{E_l}} * \frac{M}{d^2} \tag{2-13}$$

"*Illustration: Now consider that each node generates the data packets of fixed size with 512 bits. If energy required for 1-bit transmission is 50 nJ/bit then, the energy consumed by the network in communication of packets towards the sink from nodes with and without aggregation is illustrated using an example in [8] as:*

Assume that, N=12, n-4, therefore $G=\{C_1, C_2, C_3, C_4\}=\{ k_3, k_4, k_3, k_2\}$

The packet generation rate of nofes in cluster are $C_1(4,4,4)$, $C_2(2,5,6,3)$, *C3(4,4,2), C4(5,4) then,*

Number of packets without aggregation=($Ch_1 + Ch_2 + Ch_3 + Ch_4) = 47$

No of packets with aggregation = 35

*Energy consumption with aggregation = No. of packets * No. of bits/packet* Energy for transmission =* $35 * 512 * 50 * 10^{-9} = 0.90$ *m J*

Energy consumption without aggregation = $47 * 512 * 50 * 10^{-9} = 1.2$ *m J"*

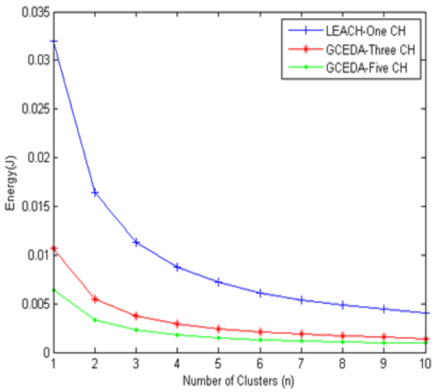
2.5.4. RESULTS AND DISCUSSIONS

The performance of GCEDA [8] is compared with the Low-energy Adaptive Clustering Hierarchy (LEACH) [26-27] protocol which uses one CH. Grouping of cluster heads in the inter-cluster aggregation shows the improvement in energy consumption. The parameters used for simulation of GCEDA uses the first order radio model from [24, 8] and are summarized in Table 2-5.

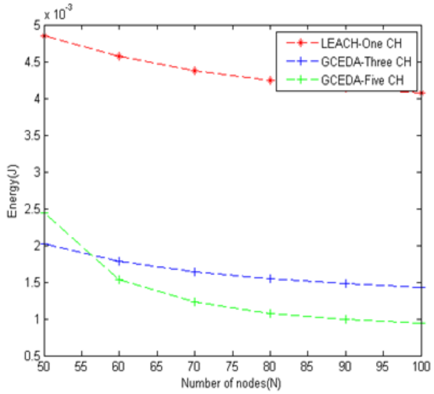
Table 2- 5 Simulation parameters- GCEDA [8]

Parameters used in Energy model	
Network Diameter	100x100 meters
Number of nodes	50-100
Length of message bits	512 bits (64 bytes) fixed
Number of Data Frames frames N_f	1000
Initial energy of nodes	100J
Transmitter/receiver electronics (E_e)	50 nJ/bit
Transmit Amplifier-short distance (E_S)	10 -100 pJ/bit/m^2
Transmit Amplifier-long distance ((E_l)	0.01310 pJ/bit/m^4
Energy for Data aggregation (E_{DA})	5 nJ/bit/signal

Figure 2-11(a) the energy variation in GCEDA[8] depends on the number of nodes and are grouped in the intra and inter-cluster aggeration. It shows that with increasing number of groups of the cluster at on-hop from the sink, the energy consumption reduces by a factor of 2% as compared to LEACH, which uses single CH. During aggregation process, the packets with same data are dropped reducing the energy consumption required to transfer packets.

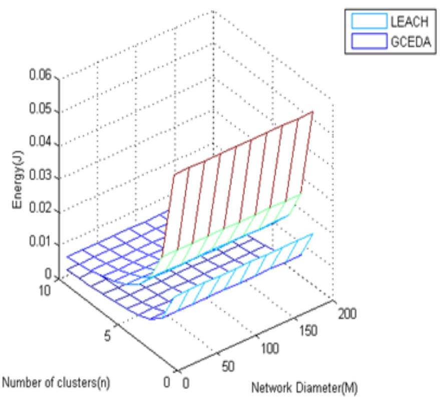


a) with a number of clusters

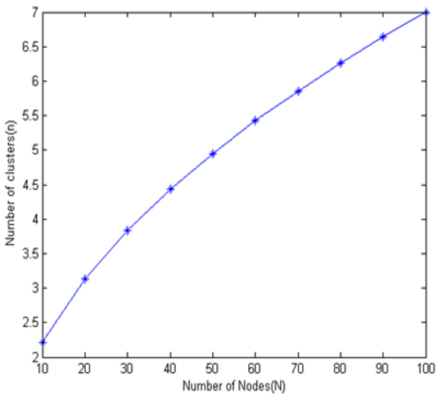


b) with increasing number of nodes

.



c) with increasing network diameter



d) Optimum number of clusters

Figure 2-11 Results of energy consumption- GCEDA [8]

Figure 2-11(b) represents the energy consumption in the network when a number of nodes are varied from 50-100 with a fixed number of CHs n=10. The nodes in the initial stage are grouped according to the packet generation capability in the cluster, so that repetition of reading is minimized. This indicates the energy consumption reduces from 47.36% to 14.94% with a group of three CHs and 21.36% with a group of five CHs as compared to LEACH.

Figure 2-11(c) indicates the effect of network diameter with the increased possibility of multihop communication between node and CH, and CH to sink. This requires extra energy to group the nodes and CHs at the intermediate levels of aggregation. If the diameter of network changes from 100-200 meters with the fixed number of nodes and CHs, then energy consumption increases approximately by 1%, since individual communication of aggregated packets from one or multi-hop requires more energy.

From Figure 2-11(d), the optimum number of clusters for effective minimization of energy are approximately seven and can extend up to 10. If cluster formation is not optimal, then the energy consumption increases exponentially either with the number of clusters greater or smaller than the optimal value. The optimal number of clusters depends on the network diameter and number of nodes[8].

2.6. SUMMARY OF CHAPTER

The perfectly compressible aggregation function at CH as intra-cluster and network-wide aggregation as inter-cluster reduces the repetitive packets and shows improvement in the energy efficiency, lifetime and throughput. The rate based aggregation works on the semantic and temporal correlations of data and packets generated by the nodes at a variable rate. It consumes more energy in a different rate of aggregation as compared to equal rate [7]. The perfectly compressible (additive and divisible) aggregation function at CH as intra-cluster and at sink as inter-cluster aggregation reduces the packet count hence throughput as compared to tree-based aggregation, which is the measure of bandwidth utilization. From the analysis, packet aggregation is more prominent than data aggregation. GCEDA [8] uses the same principle of aggregation as TTCDA but differs in the principle of operation. Also, the concept of grouping the nodes at intra- cluster and CHs at inter-cluster aggregation and communication (GCEDA) shows the reduced energy consumption by 14.94 %. But, if network diameter increases, it is increased approximately by 1%. The cluster-based network are used in WSN for data aggregation which gives best results for a scalable network with minimum variations in topology and energy consumption as compared to the tree-based [6-8].

2.7. REFERENCES

[1] R.Rajagopalan, and P.K. Varshney,“Data aggregation techniques in sensor networks: a survey,” IEEE Communication Surveys & Tutorials 8(4), pp. 48-63, 2006.

[2] Fasolo E, Rossi M, Widmer J, and Zorzi M, “In-network aggregation techniques for wireless sensor networks: a survey,” IEEE Wireless Communications,14(2), pp.70-87, April 2007.

[3] Krishnamachari L, Estrin D, and Wicker S, “The impact of data aggregation in wireless sensor networks,” 22nd International Conference on Distributed Computing Systems, pp. 575- 578, 2002.

[4] Hwa-Chun Lin, Feng-Ju Li, and Kai-Yang Wang, “Constructing Maximum-Lifetime Data Gathering Trees in Sensor Networks with Data Aggregation,” IEEE International Conference on Communications (ICC), pp. 1-6, May 2010.

[5] Marc Lee, Vincent W, and Wang S, “An energy aware spanning tree Algorithms for data aggregation in Wireless Sensor Networks,” vol.05, pp. 7803-9195, 2005.

[6] Dnyaneshwar Mantri, Neeli Rashmi Prasad, Ramjee Prasad, and Shingo Ohmori, “Two Tier Cluster-based Data Aggregation (TTDCA) for Wireless Sensor Networks,” IEEE International Conference on Advanced Networks and Telecommunication Systems, pp. 117-122, Dec. 2012.

[7] Dnyaneshwar Mantri, Neeli Rashmi Prasad, & Ramjee Prasad, “Two Tier Cluster-based Data Aggregation (TTCDA) in Wireless Sensor Network,” Springer Journal Wireless Personal Communications, 75(4), pp. 2589-2606, Nov. 2013. DOI 10.1007/s11277-013-1489-x.

[8] Dnyaneshwar Mantri, Neeli R. Prasad, and Ramjee Prasad, “Grouping of Clusters for Efficient Data Aggregation (GCEDA) in Wireless Sensor Network,” 3rd IEEE International Advance Computing Conference (IACC-2013), pp. 132-137, Feb. 2013.

[9] Karthikeyan Vaidyanathan, Sayantan Sur, Sundeep Narravula, Prasun Sinha, “Data Aggregation Techniques in Sensor Networks,” Technical Report OSU-CISRC-11/04-TR60, pp.1-10, 2009.

[10] Ameer Ahmed Abbasi, and Mohamed Younis, “A survey on clustering algorithms for wireless sensor networks,” Computer Communications, Network Coverage and Routing Schemes for Wireless Sensor Networks, vol. 30, pp.2826-2881, Oct. 2007.

[11] Kumarawadu P, Dechene D.J, Luccini M, and Sauer A, “Algorithms for Node Clustering in Wireless Sensor Networks: A Survey,” 4th International Conference on Information and Automation for Sustainability (ICIAFS), pp. 295-300, Dec. 2008.

[12] Chuan-Ming Liu, Chuan-Hsiu Lee, and Li-Chun Wang, “Distributed Clustering algorithms for data-gathering in wireless mobile sensor networks,” Journal of Parallel and Distributed Computing, 67(11), pp. 1187-1200, Nov. 2007.

[13] Wen-Hwa Liao, Yucheng Kao,and Chien-Ming Fan, “Data aggregation in wireless sensor networks using ant colony algorithm,” Journal of Network and Computer Applications, 31(4), pp. 387-401, Nov. 2008.

[14] Chuan-Yu Cho, Chun-Lung Lin, Yu-Hung Hsiao, Jia-Shung Wang, and Kai-Chao Yang, “Data Aggregation with Spatially Correlated Grouping Technique on Cluster-Based WSNs,” Fourth International Conference on Sensor Technologies and Applications (SENSORCOMM), pp. 584-589, July 2010.

[15] Huifang Chen, Hiroshi Mineno, and Tadanori Mizuno, “Adaptive data aggregation scheme in clustered wireless sensor networks,” Computer Communications, 31(15), pp. 3579-3585, Sept. 2008.

[16] Woo-Sung Jung, Keun-Woo Lim, Young-Bae Ko, and Sang-Joon Park, “Efficient Clustering-Based Data Aggregation in Wireless Sensor Networks,” Journal articleWireless Networks, 17(5), pp. 1387-1400, 2011.

[17] Wang C, Jiang C, Tang S, and Li X, “SelectCast: Scalable Data Aggregation Scheme in Wireless Sensor Networks,” IEEE Transactions on Parallel and Distributed Systems, pp. 296-300, 2011.

[18] Wei Wang, Bingwen Wang, Zhuo Liu, Lejiang Guo, and Wei Xiong, “A Cluster-based and Tree-based Power Efficient Data Collection and Aggregation Protocol for Wireless Sensor Networks,” Information technology journal, 10(3) pp. 557-564, 2011.

[19] Wenbo He, Xue Liu, and Klara Nahrstedt, “PDA: Privacy preserving dataAggregation for information Collection,” ACM Transactions on Sensor networks, 8(1), Article 6, pp 1-22. Aug. 2011.

[20] Tsitsipis D, Dima S, Kritikakou A, Panagiotou C, and Koubias S, “Data merge A data aggregation technique for wireless sensor networks,” 2011 IEEE 16th Conference on Emerging Technologies & Factory Automation (ETFA), pp. 1-4, Sept. 2011.

[21] Ma Chaw Mon Thein, and Thandar Thein, “An Energy Efficient Cluster-Head Selection for Wireless Sensor Networks,” 2010 International Conference on Intelligent Systems, Modelling and Simulation 7(10), pp.7695-3973, 2010.

[22] Curt Schurgers, Vlasios Tsiatsis, Saurabh Ganeriwal, and Mani Srivastava. “Optimizing sensor networks in the energy-latency-density design space,” IEEE Transactions on Mobile Computing, 1(1), pp. 70–80, 2002.

[23] RF Monolithics, I., TR1000 Data Sheet 1999: http://www.rfm.com/products /data/tr1000.pdf.

[24] W. R. Heinzelman, A. Chandrakasan, and H. Balakrishnan, “Energy-efficient communication protocol for wireless microsensor networks,” In Proceedings of the Hawaii International Conference on System Sciences, Maui: IEEE Computer Society, vol.2, pp. 3005-3014, Jan. 2000.

[25] Ranjan R, Kar S, “A novel approach for finding an optimal number of cluster head in wireless sensor network,” 2011 National Conference on Communications (NCC), pp.1-5, Jan. 2011.

[26] M.J.Handy,MHaase,D.Timmerrnann., “Low energy adaptive clustering hierarchy with deterministic cluster-head selection,” Proc of the 4th IEEE Conf on Mobile and Wireless Communications Networks, pp. 368-372, 2002.

[27] Yuhua Liu, Zhenrong, Luo, Kaihua Xu, and Lilong Chen, “A reliable clustering algorithm base on LEACH protocol in wireless mobile sensor networks,” 2010 2nd International Conference on Mechanical and Electrical Technology (ICMET), pp. 692-696, Sept. 2010.

CHAPTER 3. MOBILITY AND HETEROGENEITY-AWARE DATA AGGREGATION ALGORITHMS

The Data aggregation and progressive methodologies are utilized as a part of WSN applications. It helps to moderate the computational burden and information repetition for improving the energy consumption and bandwidth utilization. The chapter focuses on the application of perfectly compressible aggregation function at cluster head and sink as intra and inter-cluster aggregation. The nodes in the network generate the packets at a variable rate and consider the arbitrary data generation in the range of 0 & 1. The chapter outlines the impact of packet and data aggregations for bandwidth utilization and reduces the communication cost. As compared to present state-of-the-art solutions the proposed mechanism based on mobility and heterogeneity concept proves to be effective for throughput improvement.

3.1. INTRODUCTION

Internet of things (IoT) offers an assortment of novel applications and opens the new spaces for data aggregation utilizing Wireless Sensor Networks (WSNs) [1-2]. WSNs utilized for applications such as target tracking and border surveillance applications require numerous nodes to cover the regions and produce a lot of repetitive detecting information and consequently, results in energy and bandwidth constraints[3-4]. Additionally, WSNs in IoT with device-to-device communication demands the effective data aggregation algorithms for sending out the reliable information [3].

A heterogeneous network utilized for supporting IoT applications is shown in Figure 3-1. The principle challenge in the design of WSNs is the best possible usage of assets like energy and packet transfer speed (bandwidth), which are scarce. One approach to take care of the issue is end of repetitive information by use of aggregation at CHs and sink as intra and inter-cluster aggregation. The communication cost forced, because of repetitive information devours the lifetime, data transfer capacity (bandwidth) of nodes and network.

In this setting, the energy utilization, system lifetime, data transfer capacity (bandwidth) and transmission expense of the WSNs influence altogether. The variation in lifetime and bandwidth requirement relies on the adjustments in network topology and the strategy for aggregating the packets [4-5]. The chapter focuses on cluster-based aggregation model instead of flat since clustering enhances the adaptability by balancing out the network topology [6-7]. The heterogeneity of node expands the system lifetime and reduces the energy consumption with the static sink. However, it is challenging to aggregate the information with increased mobility of sink.

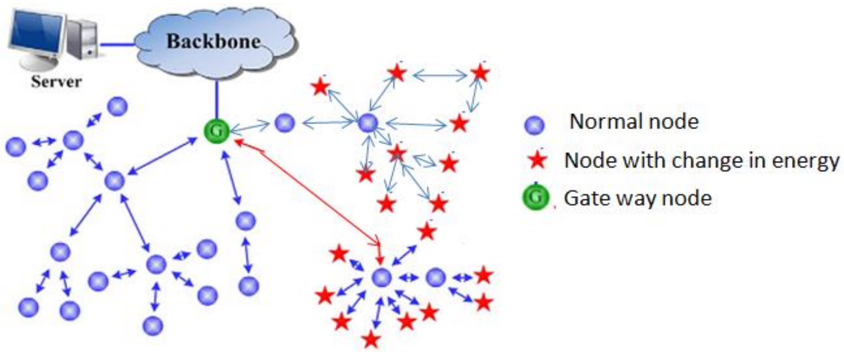


Figure 3- 1 Heterogeneous network of IoT[10]

In the hierarchical WSNs, with the random deployment of nodes, resource allocation primarily relates to the amount of bandwidth given to the CH, which may act as an aggregator or gateway in the network [7-8, 12]. The network model presented in Figure 3-2 considers the fixed region of aggregation at CHs. The perfectly compressible aggregation function (eq. 3-2) at CHs and sink uses the correlation of packets and data generated by each node at a variable rate. The two levels of aggregation as intra and inter-cluster help to save energy, improve the network lifetime and bandwidth utilization. Also, data aggregation with in-network processing makes it possible to reduce energy consumption with better bandwidth utilizations [7-12].

The challenge in cluster-based aggregation is mobility support. To address this requirement chapter has four proposals of cluster-based data aggregation algorithms: Bandwidth Efficient Cluster-based Packet Aggregation BECPA [8], Mobility and Heterogeneity-aware CDA (MHBCDA and MHCDA) [9, 10], and Bandwidth Efficient Heterogeneity aware CDA (BHCDA and BECDA) [11, 12]. The BECPA and BECDA algorithms are proposed to address the optimal aggregation of the packet and random data generated at a variable rate to improve the use of channel bandwidth and reduce energy consumption. The proposed aggregation algorithms use perfectly compressible aggregation function at CHs and sink for intra and inter-cluster communication with heterogeneous nodes, static and mobile sink. The proposed aggregation algorithms consider the correlation of packets and data within the packets. BECPA [8] consider the heterogeneous nodes with different energy level and are equal in numbers with static sink. MHBCDA [9] and BHCDA [11] algorithm uses sink mobility to aggregate the packets and data at CH within the predefined region to minimize the computation and communication cost. By reducing the number of packets reached to sink, the algorithms show better energy efficiency, reduced communication cost, improved bandwidth utilization and network lifetime when compared with state-of-the-art solutions. Finally, concludes with the comparison of results with and without sink mobility.

3.2. RELATED WORKS

The Data aggregations and hierarchical structures are regularly utilized as a part of WSNs applications. It reduces the computational burden and excess information for enhancing the energy efficiency and bandwidth utilization in the network having static heterogeneous nodes with a mobile sink. TTCDA [7] analytically proves that aggregation algorithm using differentiating aggregation function reduces the energy consumption, improves the lifetime and bandwidth utilization by removing data redundancy. The diverse metrics used in efficient cluster formation, CH election, data aggregation and communication are explored in [6, 12- 15]. To address the issues of mobility of Sink with heterogeneous nodes for improving QoS parameters of WSN are proposed in [8-12]. Mobility and Heterogeneity aware Bandwidth efficient Cluster-based Data Aggregation (MHBCDA/MHCDA) [9/10] gives the impact of mobile sink with improved bandwidth utilization and reduced energy consumption. With increased hops for aggregation of data requires more energy, particularly in the case of without mobility. Bandwidth Efficient Heterogeneity aware Cluster-based Data Aggregation (BHCDA) [11-12] use heterogeneous nodes with energy and mobile sink to aggregate data within the packet; it shows that data aggregation at CH reduces the transmission cost imposed by redundant data. Select Cast [16], explores the combination of the single and multi-hop length aggregation schemes to achieve an optimal trade-off between aggregation throughput and gathering efficiency. The multi-hop length scheme is suitable for the perfectly compressible aggregation functions like mean and max applied on the semantic data received from nodes. The algorithm presented in [17] adaptively chooses the suitable data aggregation function based on the rate of data from the nodes. It demonstrates the change in energy consumption with the speed of the target. In [18], authors consider the grouping of the cluster for reducing the energy consumption. It uses the grouping of nodes in the cluster based on equal and different packet generating capability of nodes as intra-cluster aggregation. The principle is applied for grouping of CH as inter-cluster aggregation and communication. It shows marginal improvement in energy savings up to a group of three CHs.

Stable Election Protocol (SEP) [19] and Energy-efficient Data Gathering Protocol (EDGA) [20] extend the lifetime and stability period of the network by adding heterogeneous nodes. The remaining energy and weighed election probability of node decides the CH for obtaining greater throughput. With increased node density CH election is complex and consumes more energy. EDGA constructs the routing tree to communicate the data to sink. Energy Efficient Cluster-based Data Aggregation (EECDA) [21] uses the hybrid approach of energy efficient routing and data aggregations. The controlled heterogeneity of nodes enhances the lifetime and increases the stability period. In [22], the maximum residual energy path to communicate the aggregated data to sink is chosen. Most of the data communication is in a single hop. In [23], the proposed algorithm considers homomorphic hashing and aggregation signature for lossy data aggregation and security. The aggregation node authenticates the data. Management Architecture for Heterogeneous WSN (MARWIS) [24] is heterogeneous in regards to architecture rather than energy. The presented architecture is subdivided into group of similar nodes with equal capacity and used for monitoring. The mesh network used reduces the round trip time and packet loss for efficient resource utilization. Single hop data-gathering problem (SHDGP) [25] considers the mobile data collector equipped with powerful trans-receiver and data handling and communication capability. It collects the data from single hop nodes without relay and collision and then communicates to static sink. It reduces the energy consumption and shows increased lifetime. With multihop and distance coverage number of data collector and routes need to be increased, may cause the problem of collision. [26] Explores the possibility of improving the energy efficiency by optimizing the mobility route of sink and duty cycling of node. With reduced duty cycle of node possibility of energy dissipation is reduced and increases the lifetime. Semantic Correlation Tree (SCT) [27], for data aggregation is formed using ring-like structure. It consists of the sink and sector heads responsible data aggregation and association. The doorway algorithm reduces the congestion by sending approximating sensor reading and controlling the queue size. [28] Proposes the signal compressing and data aggregation paradigm for IoT. The end node in the WSN measures and transmits the sampled data for reduced communication overheads. The problems focused in related work with regards to data aggregation algorithms are due to increased mobility patterns and heterogeneity of node.

3.3. NODE HETEROGENEITY AND MOBILITY-AWARE ALGORITHMS

In this section, we introduce the details regarding implementation of bandwidth efficient algorithms, which considers the stable and mobile sink along with heterogeneous nodes in regards to energy [8, 10]. The nodes are configured as normal nodes, advanced nodes, and supernodes and are equal in numbers. The mobility of sink is considered according to the predefined path [26]. It reduces the collision of packets since the node is active only during movement of the sink. The details of the node and network assumptions along with network model and flow of algorithm is discussed in sub-sections.

3.3.1. NODE AND NETWORK ASSUMPTIONS

The node and network level assumptions of the different algorithms used in this chapter are considered from section 2.4.1 except- Nodes used are heterogeneous in with energy and synchronized with each other. The network uses region-based aggregation and network is divided into small regions of 25 X 25 meters. Each region has one CH and randomly distributed heterogeneous nodes with equal density. The re-election of CH is not considered. The network has one mobile sink. A lifetime of the network is considered up to the first node die [8, 10].

3.3.2. NETWORK MODEL

"*The network model for the BECPA [8] and BECDA [11-12] is shown in Figure 3-2 is the extension of Figure 2-3 from section 2.4.2; it consists of a set of sources with different energy levels as a normal node, advanced node, and super node. The network model is considered as a connecting graph G (V, E) of different clusters* $\{C_1, C_2, C_3, \text{---} C_{n,}\}$ *of WSNs with heterogeneous nodes and mobile sink [7]. Each region has a CH and numbers of nodes that are represented by a set of vertices 'V' and wireless connecting edges 'E'. The 'V' nodes* $(S_1, S_2,\text{---}S_{u,\,h})$ *in the network are randomly distributed and organized into 'n' clusters using a multi-hop clustering algorithm [6, 13]. Few nodes 'h' are deployed with higher energy (30J, 40J) than the normal nodes 'u' (20J). Now consider that, each cluster has 'N' nodes out of which 'u' and 'h' nodes '*$\forall u, h \in N$*' acts as a cluster member and generates the packets* $\{r_1(t), r_2(t), r_3(t)\ \ldots\ r_{u,h}(t)\}$ *of fixed size at a variable rate [8,12]. The rate based aggregation function by adding heterogeneous nodes is given by eq. (3-1),*

$$f(A) = \{f(S_1), f(S_2), f(S_3) \ldots f(S_{u,\,h})\} \text{ i.e. } f(A) = \sum_{i=1}^{u,h} r_i(t). \tag{3-1}$$

Which consider the temporal and spatial correlations of the number of packets and random data generated by each type of nodes [8,12]."

3.3.3. AGGREGATION FUNCTIONS AND ENERGY CALCULATIONS

The perfectly compressible aggregation function used by the mobility and heterogeneity-aware packet and data aggregation algorithm at CH and sink is derived from eq. (2-2 and 2-3) Ref section 2.4.3 chapter 2. The network-wide aggregation function in eq. (3-2) combines the packets generated at a variable rate (equal and different) and random data within the packet [8, 12].

$$f(C_A) = \sum_{i=1}^{K} (X_i) + \frac{1}{M} \sum_{j=1}^{M} (Y_J) \tag{3-2}$$

Where X_i = different rate of packet generation,
Y_j = equal rate of packet generation

K= packets generated at different rate
M= packets generated at equal rate

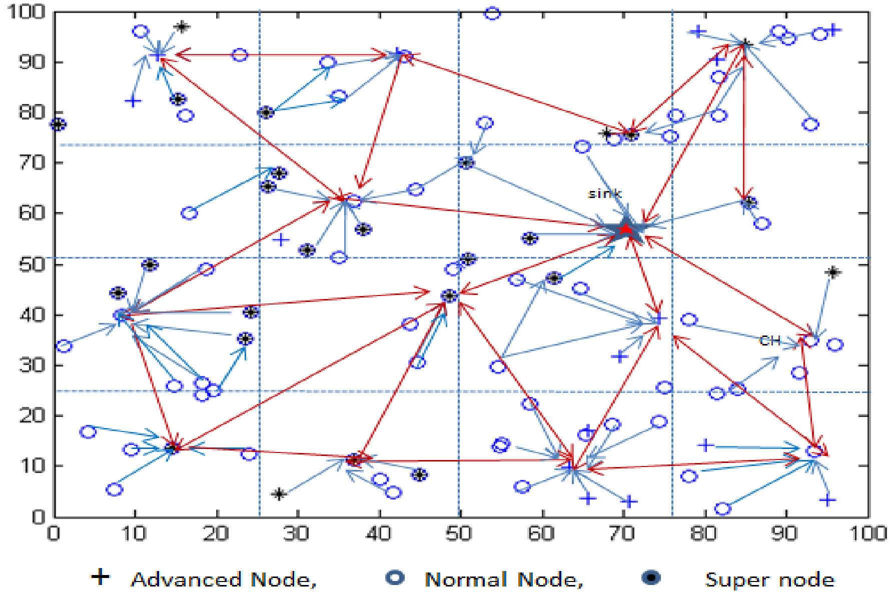


Figure 3- 2 Network model [10-12]

The aggregation functions used in BECPA and BECDA aims to increase the bandwidth utilization, reduce the communication overhead (cost) and minimize average energy consumption in the network with increased network lifetime [8, 11, 12]. The energy model used in the transfer of packets and data from CM to CHs and CHs to sink is same as used in chapter-2, section 2.5.3 and energy spend in the aggregation of packets by CH is according to [12, 18]. "*The total energy consumed by the CH (E_{ch}) in the aggregation of 'K' bit packets at intra-cluster aggregation is taken from [18] as,*

$$E_{ch}= K^* E_e (N/n) + K^*E_S d^2 + ((N/n)-1)^*K^* E_{DA}) \qquad (3\text{-}3)$$

Where 'E_{DA}' is the energy consumed in the aggregation of data packets at CH, each cluster contains the 'N/n' nodes, 'E_e' is the energy of transmitter, 'E_s' is energy consumed by the node and 'd^2' is the distance of a node to CH. Also with the consideration of heterogeneity of nodes in the network the total initial energy of network is [8, 10, 12]

$$E_i=N\,(\alpha E_n+\beta E_a+\gamma E_s) \qquad (3\text{-}4)$$

Where α = % of normal nodes with energy E_n = 20 J, β = % of advanced node with energy E_a = 30J, γ = % of supernodes with energy E_s = 40J, with equal number of nodes in the network α= β= γ=1/3 [9-12]".

The cost of aggregation at sink according to [10, 15] is

$$C_i = \sum_{j \in N_i} cost(n, CH) + cost(CH, sink) \tag{3-5}$$

This indicates the energy consumed by a cluster member 'n' to send a packet to CH and CH to sink [10].

3.3.4. FLOW OF ALGORITHM

The algorithms utilized for enhancing bandwidth utilization are considered by PDR and throughput as metric of calculations with diminishing energy consumption. It works with three phases 1. Cluster formation, 2. Intra-cluster aggregation and communication, and 3. Inter-cluster aggregation and communication as shown in Figure 3-3 [8-12].

Phase-I: Cluster formation and election of CH:

"In this phase, randomly distributed heterogeneous nodes are organized into the number of clusters according to the clustering algorithms [6, 13, and 14]. It decides the CH for intra-cluster and inter-cluster aggregation from each square region. CH is elected according to the highest energy between the cluster member (normal, advanced or super node) and the highest number of average neighbor nodes with one-hop connectivity. The threshold for the node to become CH is decided according to eq. (2-4) in chapter 2 [7]."

$$T(n) = \frac{1}{1 - p(r \bmod 1/p)} \frac{E_r}{E_i} \frac{D_i}{D_{avg}} d_v$$

Phase-II: Intra-cluster aggregation and communication:

After the election of CH, all the member nodes from the respective cluster send the fixed size packets to CH where these are aggregated by use of perfectly compressible aggregation function. The rate of packet generation varies from node to node i.e. variable. The aggregated packets at CH are obtained using algorithm 1 as discussed below

"Algorithm 1: For finding the aggregated packets in intra-cluster aggregation [8, 10]

Input: *Graph G (V, E) with 'n' clusters G = {C_1, C_2, C_3, - - C_n}, one sink.*

Output: *CH with aggregated packets and sink with network-wide aggregation*

Step1: Generation of Packets and data at a variable rate

Step2: Perform Intra-cluster aggergation according to the PGR

Step3: Forward the packets to CH

Step4: Otherwise store it and compare with incoming packets

Step6: Perform aggregtaion at CH

Step7: Collection Phase:

{

If (packet reaches to aggregator)

Store into routing table

If (previous packet/ data= next packet/ data) then

Drop the packet/data (no aggregation)

else

Wait for T sec/count

If (T=0 and Count ≠ 0) then

Apply perfectly compressible aggregation function

else

Wait for T=0

end if ”

Step8: Repeat the Steps 3 to 7

Phase-III: Inter-Cluster Aggregation and Communication

According to the network consideration, each CH in the third phase works as an individual node for performing inter-cluster aggregation. The result is the aggregation of data packets at the sink with reduced packet count, thus reducing communication cost [8, 10, 12]. “*Let C_i denotes the cost of cluster formation by CH node ‘i’ with its neighbor ‘N_j’. The CH performs the primary aggregation and forwards aggregated packets to sink with inter-cluster aggregation. The network [Node – CH - Sink] wide cost of communication is calculated according to [8, 10, 15] and is given by eq. (3-6).”*

$$C(j, sink) = \sum_{j \in N_i} cost(j, i) + cost(i, sink) \tag{3-6}$$

This indicates the cost of aggregation in terms of energy consumption by the network, where cluster members send random packets to CH [cost (*j*, *i*)] and CH to sink [cost (*i*, *sink*)].

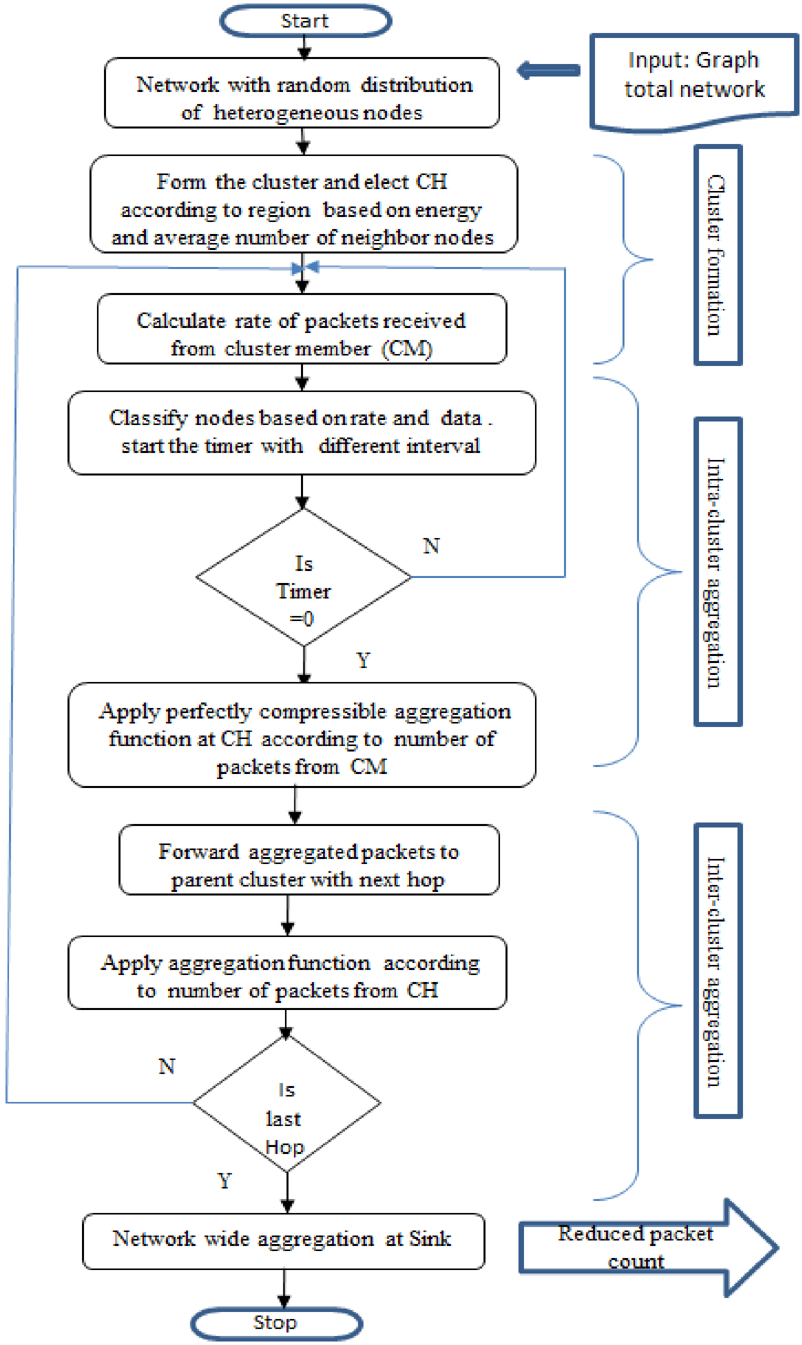


Figure 3-3 Flow of algorithms- BECPA [8] and BECDA [12]

In this phase, graph G includes the sink and all participating CH as G = {Ch_1, Ch_2, --- Ch_n} with all V {Ch, sink} and *Ec* are the connecting edges between all the CHs and the sink.

The algorithm 2: used for aggregation of packets in the inter-cluster stage is found in [12]. The algorithm, first runs for all the CH to aggregate the packets and then same procedure is repeated for the inter-cluster with increased hop-count from the CH to sink for transfer of data /packets.

Algorithm 2: For finding the aggregated packets in inter-cluster aggregation [12]

Input: *Graph G (V, E) with 'n' clusters G = {C1, C2, C3, - Cn}*

Output: *CH with aggregated data packets and sink with network-wide aggregation.*

"***Notations:*** *hc= hop count, S-Sink, Pam- Parent announcement messag, Pch-Parent cluster head, Rt- Routing table,*

1. *Sink node generates Parent Announcement message (Pam)*
2. *Set parent CH id = sink id*
3. *Set first Pam=hc=1 and previous hop= sink id*
4. *Initialize the timer for periodically broadcast Pam*
5. *If CM receives Pam, then update the routing table Rt=Pam= previous sink id, since hc=1*
6. *Increment hop count hc=hc+1 and update Pam=current node id*
7. *Else, check the sequence number in 'Rt' and update 'hc'*
8. *If new-forward to Pch, else drop the packet*
9. *Classify the nodes based on the rate*
10. *At the end of time interval calculate rate of data received from CM*
11. *Aggregate number of packets received and sent it to CH*
12. *Repeat steps 4 to 11 till packet reaches to the sink*
13. *End "*

3.4. RESULTS AND DISCUSSIONS

The performance of the data aggregation algorithms with heterogeneous nodes with and without sink mobility is evaluated with two conditions of packet generation. Each node in the network may generate the packet with equal rate (ER) or different rate (DR). Also, data required for the aggregation is generated by each node using random function and is in the range of 0-1. "The results obtained for different performance" measures of BECPA [8, 12] (without sink mobility) and BECDA [11-12] (with sink mobility) are compared with TTCDA [7] and EECDA [21]. To validate the performance, network simulator NS-2 is used with a random distribution of nodes in a given area. Transmit and receive power of WSN nodes are taken according to trans-receiver model TR1000, simulation parameters used are listed in Table 3-1."

Table 3- 1 Simulation parameters [8-12]

Parameter	Value
Network size	100 x 100 meters
Number of nodes	100
Energy of heterogeneous nodes	20J,30J,40J
Placement of node	Random
Initial energy of sink	100 J
Propagation model	Two ray-Ground
Traffic model	Constant bit rate
Packet size	64 bytes
Ideal power	14.4mW
Transmission power	36.0mW
Receiving power	12.5mW
Simulation time	500 sec
Packet generation rate (PGR)	0.02-0.2kb
Sink mobility	10 meters/sec

3.4.1. RESULTS WITH NODE HETEROGENEITY AND STABLE SINK: BECPA [8]

The BECPA algorithm aims to reduce the energy consumption with reduced packet count for improving bandwidth utilization using packet aggregation. It uses the stable sink with heterogeneous nodes [8, 10]. "*It is assumed that nodes are heterogeneous and part of the network graph G with 'N/n' number of nodes into each cluster ($n \in u$, h). Let P denote the set of all packets received by the CH from the nodes within the region R. CH performs the aggregation on the packets arrived at t =0 and calculated effective count Cp >0. Let $f_p(t)$ denote the number of packets aggregated at time t>0. The state of CH at time't' is denoted by its vector $f(t)=\{f_p(t)\}$[10]. Note that each node u, h $\in$ R will transmit a packet to CH with a set of active links (u, h, CH). Let 'P_s' denote the set of all possible packets received, P(u, h) denote the set of packets transmitted when node 'u, h' are active [8, 10]. Therefore, an intra-cluster aggregation function based on the current number of packets from nodes at time t calculated according to eq.(3-7) [8, 10].*"

$$f(P_s, CH) = \sum_{p \in P} C_p \{ p(u,h) \in R,\ f_p(t) = CH \} \tag{3-7}$$

And the energy consumed by the CH to transfer the aggregated packets according to [18] is given in eq.(3-8)

$$E_{ch} = K^* (E_e + E_S d^2) \quad (3\text{-}8)$$

The performance of data aggregation algorithm to compete with bandwidth utilization are discussed without sink mobility and heterogeneous nodes

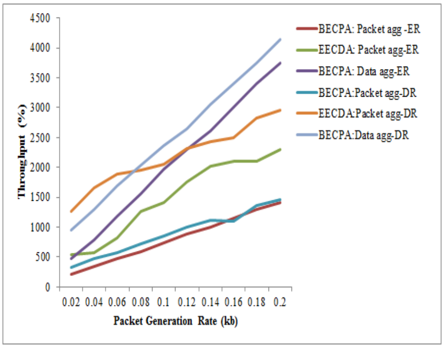
Throughput: It is the measure of how many packets received by the sink after complete round of aggregation. With varying rate of packet and data generation and application of impeccably compressible aggregation function on the number of packets reached to CH and sink, BECPA achieves around 61.45% and 64.47%, and 46.20% and 60.53% less throughput in packet aggregation as compared with data aggregation and EECDA as shown in Figure 3-4(a). It shows that data aggregation and EECDA consumes more bandwidth as compared with BECPA. This is due to EECDA using different packet and data rate generation.

Average Energy Consumption: Figure 3-4(b) demonstrates that, for the packet aggregation the average energy consumption is reduced by 3.85% and 4.67% than EECDA and saves 6.71 % of energy with an equal rate than different rate of packet generation. It also shows small change (0.41% and 0.45%) with data aggregation. It is the measure of the ratio between sums of energy consumption of all nodes to the total number of nodes. In rate based aggregation energy required for communication is less than the computation.

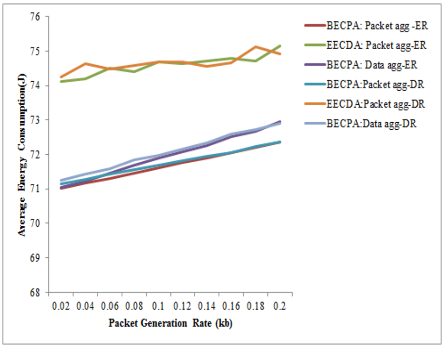
Packet Delivery Ratio: With variation in the packet generation rate from 0.02 to 0.2 Kb/packets under equal and different rate, the BECPA has reduced PDR of 60.73% and 64.51%, and 50.42% and 65.29% as compared with data aggregation and EECDA. The perfectly compressible aggregation function at sink removes the repeated data packets. The packets received by sink are less with an equivalent rate as compared to a different rate as shown in Figure 3-4(c). Less number of packets reaching to sink consumes less bandwidth. PDR is characterized as the proportion of the total number of packets received by the sink to the total number of the aggregated packets generated by all the nodes.

Residual Energy: Figure 3-4(d) shows remaining amount of energy after each round of aggregation in the network. BECPA with packet aggregation has less number of packets reached to sink. The corresponding energy saving of BECPA is increased by 1.08% and 7.73% in equal rate and 1.2% and 8.78% in diverse rate as compared to data aggregation and EECDA respectively.

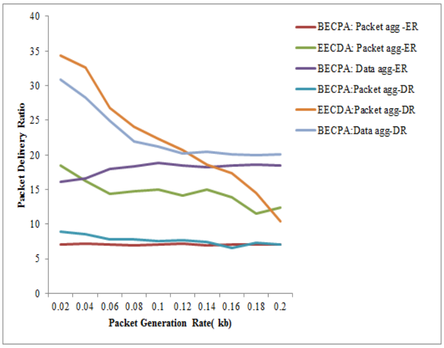
Network Lifetime: Figure 3-4 (e) indicates the network lifetime; it is the measure of how long network sustains and sink receives the last packet after the first node die. A lifetime of BECPA is more by 40.42% and 36.77% as compared with EECDA. With consideration of rate-based aggregation the lifetime of BECPA is more by 0.4% correlation with the equal rate, however, less by 6.11% in different rate. The improvement of lifetime is less in data aggregation as compared to EECDA due to randomized packet generation rate of EECDA. Also, addition of heterogeneous nodes in the network increases the lifetime.



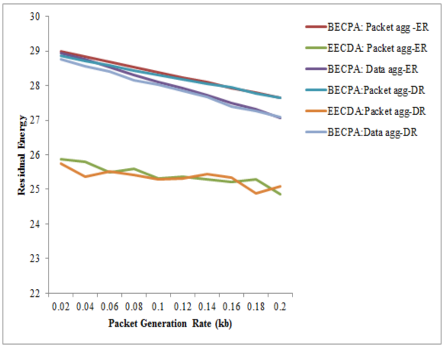
(a) Throughput-BECPA



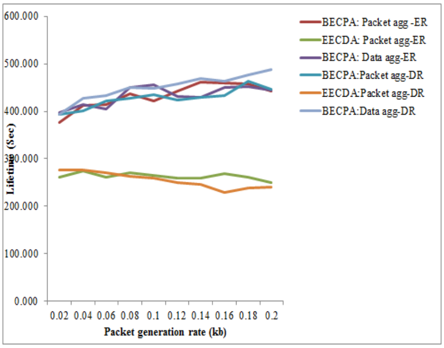
(b) Average energy consumption-BECPA



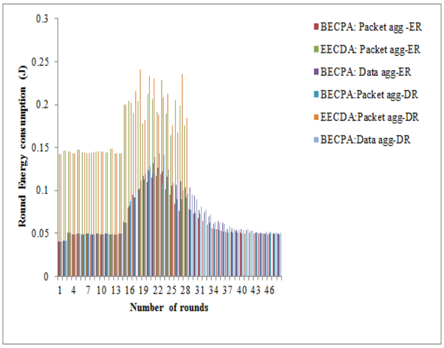
(a) Packet delivery ratio-BECPA



(b) Residual energy-BECPA



(e) Network lifetime-BECPA



(f) Round energy-BECPA

Figure 3- 4 Results with node heterogeneity and without sink mobility– BECPA [8]

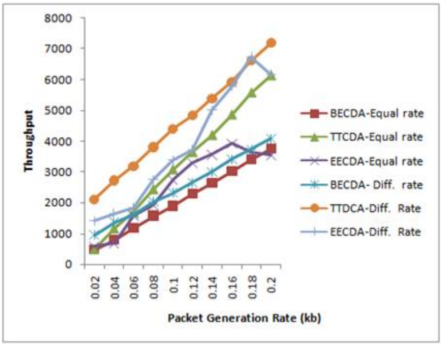
Round Energy: According to Figure 3-4 (f) up to 14th round of data aggregation the energy consumption in packet and data aggregation is same due to the addition of a heterogeneous node. The round energy goes on changings up to 37th round due to increased packet generation rate and energy drain from normal node as compared to advanced and super. In case of EECDA, network can sustain up to 28 rounds, due to random packet generated.

3.4.2. RESULTS WITH NODE HETEROGENEITY AND MOBILE SINK: BECDA [11, 12]

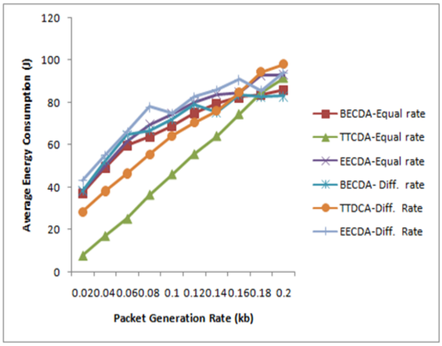
Mobility and Heterogeneity-aware Bandwidth Efficient Cluster-based Data Aggregation Algorithm (MHCDA/BECDA) [10/12] aims to improve the bandwidth utilization by controlling the number of transmissions of repetitive data packets from nodes to the mobile sink. Each node in the network generates data by use of a random function with the standard deviation in the range of 0 and 1[12]. Due to the addition of mobile sink the routing table continuously changes and need to find the travel time for the packets hop by hop. The sink is moved at the constant rate by predefined path. The results are obtained by consideration of packet and data aggregations in WSN; the packets are generated at a variable rate, and data is generated by use of the random function. The perfectly compressible aggregation function applied at CH [7], and sink improves the network lifetime and throughput with reduced energy consumption.

Throughput: It depends on the number of bits received at the sink after intra and inter-cluster aggregation in terms of packets of fixed size. With variation in the PGR from equal to different rate, the average throughput of BECDA is reduced by 37.01% and 17.16% and 45.48% and 34.39% as compared to TTCDA and EECDA respectively shown in Figure 3-5(a). This is caused due to the elimination of repetitive readings of the data packets with a mobile sink. Mobile sink pulls the packets from the nodes at one hop in the specified path. Throughput is the metric of specifying the bandwidth utilization. BECDA is bandwidth efficient as concern with TTCDA and EECDA.

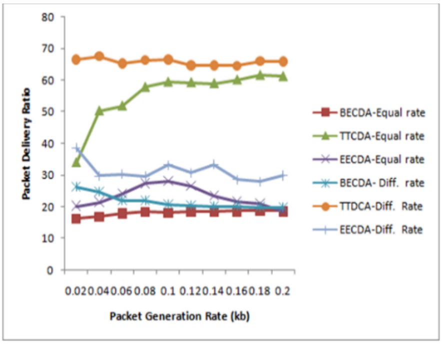
Average Energy Consumption: Figure 3-5(b) demonstrates the points of average energy consumption. It depends on the distance of node from the CH for intra-cluster aggregation and CH to sink in inter-cluster aggregation, since more energy is consumed in communication rather than computation. The average energy consumption of BECDA is less by 5.89% and 7.77% as compared with EECDA, however more by 36.29% and 6.38% as compared with TTCDA in both the conditions of data generation. The reason behind this is, EECDA utilized the static sink and more energy is required for defining the path for the accumulation of data, while TTCDA had a uniform distribution of nodes with equal data handling capability.



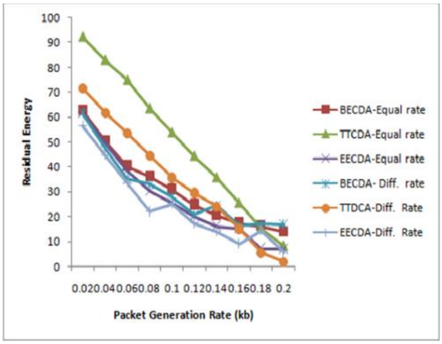
(a) Throughput-BECDA



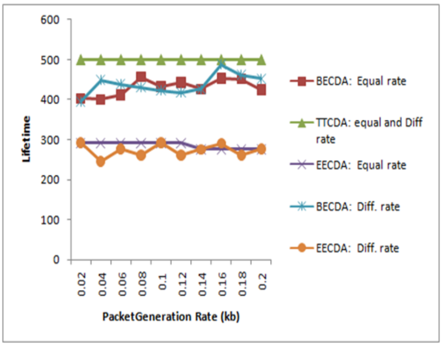
(b) Average energy consumption-BECDA



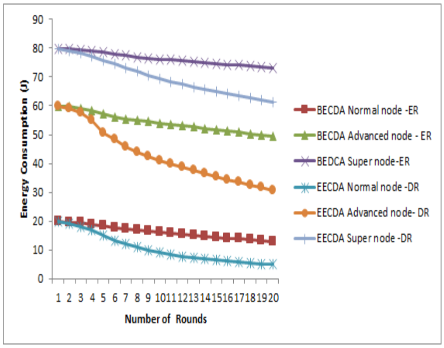
(c) Packet delivery ratio-BECDA



(d) Residual energy-BECDA



(e) Lifetime-BECDA



(f) Round energy node -BECDA

Figure 3- 5 Results with node heterogeneity and sink mobility- BESDA [11-12]

Packet Delivery Ratio: It is the measure of effective packets collected by the CH and Sink in the process of network-wide aggregation. By changing the data generation BECDA achieves less PDR of 67.66% and 22.73% and 67.29% and 30.85% (ER and

DR) as compared to TTCDA and EECDA shown in Figure 3-5(c). It also reflects on the bandwidth utilization and energy consumption of nodes.

Residual Energy: With the added advantage of sink mobility energy required to collect the packets at one hop is reduced. In diverse rate of data generation and heterogeneous environment, BECDA has more residual energy (15.77% and 24.26%) as compared with EECDA but less by approximately 36.69% and 12.19% as compared with TTCDA shown in Figure 3-5(d). It is because TTCDA considers the node with equal initial energy and without sink mobility. In the case of EECDA, most of the energy is consumed in deciding the path and aggregation strategy. Residual energy is calculated as the ratio of the sum of remaining energy of all nodes to the total number of nodes.

Network Lifetime: It is measured according to the residual energy after each round and last packet received when network is operational. Proposed BECDA with movable sink and heterogeneous nodes the lifetime is increased by 32.72% and 36.17% as compared with EECDA with the equal and different rate of packet generation as shown in Figure 3.5(e). The lifetime of TTCDA is more since it energy efficient as compared with BECDA and EECDA.

Round Energy of Nodes: With diverse capacity of nodes with initial energy, the round energy consumption of normal nodes is less as compared with super node. It happens due to involvement of super node as CH and aggregates the packets from other nodes. Super nodes help to prolong the network lifetime. The round energy of each node varies approximately by a factor of 2 from the normal node to super node. It is also seen that energy consumption of node in EECDA is less in each round as compared with BECDA.

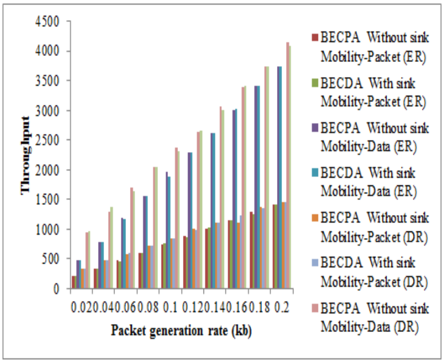
3.4.3. RESULTS WITH AND WITHOUT SINK MOBILITY

This part of the thesis gives the details of the comparative measures with and without sink mobility.

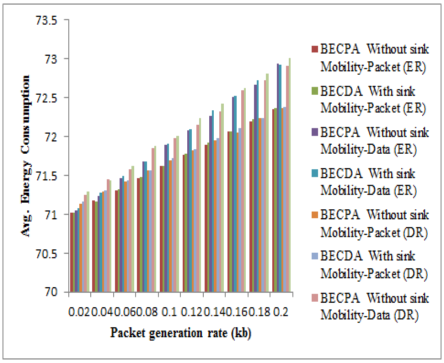
Throughput: From Figure 3-6 (a), application of the perfectly compressible aggregation on the packets received from the nodes at a multi-hop distance increases the packet count in static sink specifically in inter-cluster aggregation where individual CH contributes as node with diverse packets. With sink mobility, semantic information received by the sink from nodes at one hop is directly dropped reducing the throughput and communication load on channel i.e. better utilization of bandwidth.

Average Energy Consumption: With static sink the average energy consumption of the individual node varies and nodes close to the sink drains more energy due to heavy load of packets. As seen from Figure 3-6 (b), the average energy consumption with sink mobility is less due to one hop data collection and changing duty cycle of nodes. Also, it varies in different rate of PGR compared to the equal rate. The mobile sink improves the energy dissipation as compared to static sink.

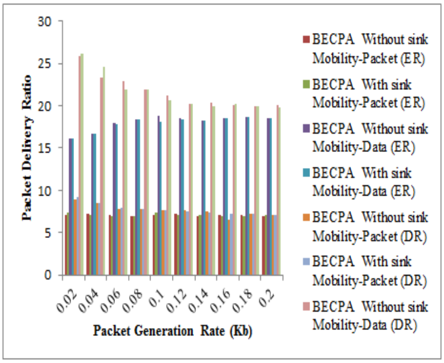
Packet Delivery Ratio: From Figure 3-6 (c), it is seen that with an equal rate of packet and data generation PDR is approximately same but shows improvement of 1.2% in the different rate of packet generation with sink mobility.



(a) Throughput



(b) Average energy consumption



(c) Packet delivery ratio

Figure 3- 6 Results with and without sink mobility [8, 10-12]

3.5. SUMMARY OF CHAPTER

The chapter proposed the data aggregation algorithms by considering the static, mobile and heterogeneous scenario of nodes and sink. The perfectly compressible aggregation function used by BECPA and BECDA shows improvement in the throughput and energy consumption. From results, it can be seen that the packet aggregation is more effective than data aggregation for efficient utilization of bandwidth. Also, with added heterogeneity to node the network lifetime increases. With the mobility of sink the throughput increases and consumes more bandwidth, but it is cost effective in regards to energy. The BECPA uses the static node and sink and has energy saving of (4.47%), BECDA considers the sink mobility and has energy saving of 8.24% as compared to EECDA but lacks with TTCDA. MHBCDA/MHCDA uses the network with heterogeneous node and mobile sink for packet aggregation. It has better energy saving (4.11%). The mobile sink improves the energy dissipation as compared to static sink. The addition of heterogeneous nodes and providing mobility to node and sink performance of the network improves with communication cost, bandwidth utilization, network lifetime and reduced energy consumption.

3.6. REFERENCES

[1] L. Mainetti, L. Patrono and A. Vilei, "Evolution of wireless sensor networks towards the Internet of Things: A survey," 19th International Conference on Software, Telecommunications and Computer Networks (SoftCOM), 1(6), pp. 15-17, 2011.

[2] Yang Zhou, Chuan Huang, Tao Jiang, and Shuguang Cui, "Wireless Sensor Networks and the Internet of Things: Optimal Estimation with Non-uniform Quantization and Bandwidth Allocation," IEEE Sensor Journal, 13(10), pp. 3568-3574, Oct. 2013.

[3] V. Gungor and G. Hancke, "Industrial Wireless Sensor Networks: Challenges, design principles, and technical approaches," IEEE Trans. Ind. Electron., 5610), pp. 4258–4265, Oct. 2009.

[4] R.Rajagopalan, and P.K. Varshney, "Data aggregation techniques in sensor networks: a survey", IEEE Communications Surveys & Tutorials; 8(4), pp. 48-63, 2006.

[5] B. Krishnamachari, D. Estrin, and S. Wicker, "The impact of data aggregation in wireless sensor networks," Distributed Computing Systems Workshops Proceedings; pp. 575- 578, 2002.

[6] Ali Chamam, Samuel Pierre, "A distributed energy-efficient clustering protocol for wireless sensor networks," A Journal of Computers & Electrical Engineering, 36(2), pp. 303-312, 2010.

[7] Dnyaneshwar Mantri, Neeli Rashmi Prasad, & Ramjee Prasad, "Two Tier Cluster-based Data Aggregation (TTCDA) in Wireless Sensor Network," Wireless Personal Communications, 75(4), pp 2589-2606, Nov. 2013.

[8] Dnyaneshwar Mantri, Neeli Rashmi Prasad, & Ramjee Prasad, “BECPA: Bandwidth Efficient Cluster-Based Packet Aggregation in Wireless Sensor Network,” Wireless Personal Communication, 76(3), pp.335-349, March 2014.

[9] Dnyaneshwar Mantri, Neeli Rashmi Prasad and Ramjee Prasad, “MHBCDA: Mobility and heterogeneity-aware bandwidth efficient Cluster-based Data Aggregation for Wireless Sensor Network,” 2013, 3rd International Conference on Wireless Communications, Vehicular Technology, Information Theory and Aerospace & Electronics Systems (VITAE), pp. 1-5, June 2013.

[10] Dnyaneshwar S. Mantri, Neeli Rashmi Prasad, and Ramjee Prasad, “Mobility and Heterogeneity-Aware Cluster-based Data Aggregation for Wireless Sensor Network,” Springer Journal-Wireless Personal Communication, 86(2), pp. 975-993, Jan. 2016.

[11] Dnyaneshwar Mantri, Neeli Rashmi Prasad, Ramjee Prasad, “BHCDA: Bandwidth Efficient Heterogeneity aware Cluster based Data Aggregation for Wireless Sensor Network,” 2nd International Conference on Advances in Computing, Communications and Informatics (ICACCI2013), pp. 1065-1069, Aug. 2013.

[12] Dnyaneshwar S. Mantri, Neeli Rashmi. Prasad, & Ramjee Prasad,“Bandwidth Efficient Heterogeneity aware Cluster based Data Aggregation for Wireless Sensor Network,” Elsevier Journal of Computer and Electrical Engineering, vol 41, pp. 256–264, Jan. 2015.

[13] Ameer Ahmed Abbasi, and Mohamed Younis, “A survey on clustering algorithms for wireless sensor networks,” Computer Communications, Network Coverage and Routing Schemes for Wireless Sensor Networks, 30(14), pp. 2826-2841, 2007.

[14] A. Bari, A. Jaekel and S. Bandyopadhyay, “Clustering Strategies for Improving the Lifetime of Two-Tiered Sensor Networks,” Elsevier, Computer Communication Journal, 31(14), pp. 3451-3459, 2008.

[15] Zhong-Gao Sun, Zi-Wei Zheng, Shao-Juan Xu, and Shao-Hua Chen, “Energy-aware data gathering protocol for wireless sensor networks,” 2010 3rd IEEE International Conference on Computer Science and Information Technology (ICCSIT), vol.7, pp. 103-107, July 2010.

[16] C. Wang, C. Jiang, S. Tang, and X. Li., “SelectCast: Scalable Data Aggregation Scheme in Wireless Sensor Networks,” IEEE Transactions on Parallel and Distributed Systems, 23(10), pp. 1958-1969, 2011.

[17] Woo-Sung Jung, Keun-Woo Lim, Young-Bae Ko, Sang-Joon Park, "Efficient Clustering-Based Data Aggregation in Wireless Sensor Networks," Springer Journal on Wireless Networks, 17(5), pp. 1387-1400. 2011.

[18] Dnyaneshwar Mantri, Neeli R. Prasad, and Ramjee Prasad, "Grouping of Clusters for Efficient Data Aggregation (GCEDA) in Wireless Sensor Network," 2013 IEEE 3rd International Advanced Computing Conference (IACC-2013) pp. 132-137, 2013.

[19] S. Georgios, Ibrahim Matta, and Azer Bestavros, "SEP: A Stable Election Protocol for clustered heterogeneous wireless sensor networks," Computer Science Department, Boston University, Technical Report BUCS-TR-2004-022; pp. 1-11. 2004.

[20] Y. Mao, Z. Liu, L. Zhang, and X. Li, "An Effective Data Gathering Scheme in Heterogeneous Energy Wireless Sensor Networks," Proceedings of International Conference on Computational Science and Engineering, pp. 338-343, 2009.

[21] D Kumar, T.C. Aseri and R B Patel, "EECDA: Energy Efficient Clustering and Data Aggregation Protocol for Heterogeneous Wireless Sensor Networks," International Journal of Computers Communications & Control, 6(1), pp. 113-124, 2011.

[22] Li Han, "An energy efficient routing algorithm for heterogeneous wireless sensor networks," 2010 International Conference on Computer Application and System Modeling (ICCASM), 3(0), pp. 612-616, 2010.

[23] Shufen Niu, Caifen Wang, Zhixuan Yu, Suzhen Cao, "Lossy data aggregation integrity scheme in wireless sensor networks," Computers & Electrical Engineering, 39(6), pp. 1726-1735, 2013.

[24] W Gerald, A Markus and B Torsten, "MARWIS: A Management Architecture for Heterogeneous Wireless Sensor Networks," WWIC LNCS 5031, pp. 177–188, 2008.

[25] Ming Ma; Yuanyuan Yang; Miao Zhao, "Tour Planning for Mobile Data-Gathering Mechanisms in Wireless Sensor Networks," IEEE Transactions on Vehicular Technology, 62(4), pp. 1472-1483, 2013.

[26] Majid I. Khan, Wilfried N. Gansterer and Guenter Haring, "Static vs. mobile sink: The influence of basic parameters on energy efficiency in wireless sensor networks," Computer Communications vol 36, pp. 965-978, 2013.

[27] S. Manoj Kumar and N. Rajkumar, "SCT Based Adaptive Data Aggregation for Wireless Sensor Networks," In Springer link, Wireless Personal Communications, 75(4), pp.2121-2133, Oct 2014.

[28] Shancang Li, Li Da Xu, Xinheng Wang, "Compressed Sensing Signal and Data Acquisition in Wireless Sensor Networks and Internet of Things," IEEE Trans. on Industrial Informatics, 9(4), pp. 2177-2186, Oct 2013.

CHAPTER 4. SCHEDULING ALGORITHMS FOR EFFICIENT BANDWIDTH UTILIZATION IN WSN

The chapter proposes the hierarchical cluster-based mechanism and discusses the system model based on the myopic and non-myopic state of the channel. For improving the throughput and energy consumption, myopic scheduling is used for intra-cluster and non-myopic scheduling for the inter-cluster communication. The collision of aggregated packets is reduced by allocating the conflict-free slots by considering present and predicted future state of the channel. The activities of nodes and aggregated packets are scheduled using TDMA as basic MAC protocol. The chapter also focuses on the trade-off between reliability and energy efficiency by combination of CSMA/CA and TDMA techniques [9]. The contribution of the chapter is the proposal of scheduling algorithms by considering static and mobile scenarios of nodes and sink. The multipath data propagation techniques used helps to increase the throughput (bandwidth utilization), a decrease in delay, collisions, retransmission of packets and the energy consumption as compared to the state-of-the-art solutions. The throughput is considered as the measure of bandwidth utilization.

4.1. INTRODUCTION

The WSNs used in the applications considering the static scenario as environmental monitoring and mobile scenario as healthcare monitoring and vehicle tracking requires increased bandwidth and energy. However, the most deciding attribute of WSNs node are its limited resources like energy, bandwidth, and memory [1-2]. The communication capabilities of node is an important factor for many real-time applications that relates to efficient utilization of bandwidth and energy. Also, network need to maintain the accuracy of the collected data, so that it remains operational with increased lifetime [2]. In WSN, data or packet communication to sink from node and CH is in multi-paths at a time, and is the main source of a collision causing increased energy consumption and delay. Depending on the requirement, packets causing a collision is either retransmitted or discarded within the restricted time demands more bandwidth and requires increased energy. At the initial stage of algorithm the packets are aggregated by use of perfectly compressible aggregation function, which removes the redundancy and reliable data packets are forward to sink [3, 4]. With increased number of packets from the nodes the time required to schedule those in channel increases required bandwidth and delay. The potential reasons for energy consumption, increased bandwidth and delay are: first, slot idle due to less number of packets from nodes and CH; secondly, increased number of packets in allocated schedule causing a collision and require retransmission; third, the decision of scheduling based on traffic load. This enforces the need of scheduling algorithm to overcome the losses by taking into account the present and predicted future state of the channel [5-7]. The scheduling algorithms are helpful in WSN for efficient use of resources. Based on the working functionality these are classified as contention based or schedule-based. The main challenges for contention-based scheduling algorithms are reducing energy consumption, collisions and improving throughput due to lack of communication. A schedule-based mechanism differs from a contention-based by assigning collision-free time slots for transmission, which reduces the energy consumption and guaranteed throughput due to coordinated access to the channel at any time for all nodes [6].

The primary task of a TDMA scheduling algorithm is to decide conflict-free schedules depending on the network topology, variable traffic loads and availability of link bandwidth [5, 7-9]. A good TDMA scheduling algorithm should assign optimal schedules by reducing the contention in the network. The other significant challenges in TDMA scheduling are assigning the optimal schedules with maximum reuse of the slots, scaling to changes in the network dynamics, providing tight synchronization in the network and supporting mobility. Also, for continuous operation and increased efficiency of WSN a transmission reliability and energy consumption are two critical concerns [9].

This chapter addresses the challenges in the allocation of conflict-free TDMA schedules by the proposing the cluster-based myopic and non-myopic algorithm (CMNS) [7], which uses static nodes. An Efficient Schedule-based Data aggregation with Node Mobility (SDNM) [8] uses mobile nodes to alleviate the problems stated above. The non-myopic schedule is useful in inter-cluster communication requiring more accuracy with node mobility [8]. The work is also extended by considering sink mobility as CMNMS algorithm. The simulation under different scenario (static nodes, mobile nodes, and mobile sink) showed that, with variable PGR and applied conflict-free TDMA schedule improves throughput, delay and energy consumption.

The final contribution of chapter proposes Schedule-based Collision Avoidance (SCA) [9] algorithm, which uses hybrid approach of CSMA/CA and TDMA technique to avoid collisions with multi-hop communications. It finds the trade-off between reliability and energy efficiency of the network by analyzing different scheduling techniques. It reduces collisions and improvs the network lifetime [8-9].

4.2. RELATED WORKS

TDMA scheduling mechanisms are divided according to usage and network management as flat or clustered WSNs. The problem with the flat WSNs is that they are not sufficiently energy efficient and lack performance in delay and scalability. The current research trend is to achieve TDMA scheduling using clustering, which has proven to be an efficient approach for achieving improved energy efficiency with decreased delays and increased scalability [7-8,15].

In [8, 10], the use of topological variations as star, mesh and cluster-based bandwidth allocation and scheduling techniques are explored. The more emphasis is on the allocation of communication bandwidth as Guaranteed Time Slot (GTS). Also bandwidth allocation on traffic, which may be busty, periodic or a periodic is considered depending on the interference of neighboring nodes channel. In multi-hop data communication, comparative study reveals that CSMA scheduling requires more bandwidth as compared to TDMA. In [11], the low data rate application with homogeneous network is considered where energy is consumed in transition. To achieve good energy efficiency dynamic activities of the nodes are scheduled according to the states of the radio using TDMA as basic MAC. The scheduling approach of allocating consecutive time slots improves energy consumption by twice than the optimized approach. It also proposes the data aggregation tree to improve throughput. Distributed TDMA Scheduling Protocol (DATP) [12] use the realistic neighbor node interference model to avoid the collision of packets in the allocated scheduling slot by transmitting dummy packet with in tolerable limits. The network is simulated for different sizes with increased node density and node contend for free slot. The limitation is unknown node interference causing overheads increasing energy consumption. [13] Explores the energy and time efficiency as one of the key measures in data collection with multipath routing structures and scheduling the activities of the node. It also provides the means of lower bound with shortest data length for reducing energy consumption. A Distributed Randomized time slot scheduling algorithm (DRAND) [14] decide schedules on the present state of the information.as with increased traffic load schedule access is preferred while during low loads random access under static condition of network. The slot assignment is random and does not require any time synchronization. The packet collisions are reduced from the nodes at two-hop neighbors without mobility. Green Conflict Free (GCF) [15] considers the conflict graph to achieve better slot sharing and reuses of slots. It improves the scalability and energy efficiency by finding the conflict-free TDMA scheduling slots for the three hop neighbors to transfer the message and reduce collisions. In Adaptive DRAND (A-DRAND) [16] with increased node density it difficult to maintain the energy balance in the network. For collision-free data transfer CH is assigned more slots, while other members alter the role of CH after specified time interval to balance the energy. This reassignment of slots increases the overheads. [17] Presents the hybrid MAC (both TDMA and CSMA) to improve the energy consumption, PDR and network lifetime of WSN with mobile nodes. The frame size used for transfer of data and control message using TDMA and CDMA adaptively incorporate the changes in mobility and traffic conditions. All the nodes used in the network are synchronized with allocated slots. In [18], the layered approach of clusters with a specific number of nodes is used for maintaining the minimum delay and maximum accuracy while aggregating the data. It improves the end-to-end delay and energy consumption with the required accuracy. On demand, Converge cast scheduling Protocol (OCS) [19] is a centralized multi-hop conflict-free scheduling protocol utilizes the request mechanism for slot assignments using TDMA to active nodes. [20] Gives the basis for testing the energy consumption under mobility pattern of single node in real time environment. Dynamic Multilevel Priority (DMP) packet scheduling [21] considers the hierarchical level for scheduling the packets in TDMA. It maintains the three levels of queues on the basis of data types as real time, non-real time remote and non-real time local. The performance of network degrades with mobile nodes since packet generation is random and served on the shortest job first. [22] Considers hierarchical and cluster-based network with the node and sink mobility. Nodes are classified according to the function as gateway, ordinary or CH for energy saving and increasing the lifetime. Due to the mobility of both sink and nodes, the possibility of link failure increases causing more energy requirements. [23] Considers the formation of network structure based on the data collection points. It gives reduced delay in communication of data when sources are nearby of each other. [24] Presents the use of TDMA MAC protocol for short-range data communication with little overheads and communication errors as compared to CSMA. [25] Presents the survey of CSMA protocol for WSN showing selection on the basis of different environmental conditions.

In summary, related work proposes the different methods for achieving the energy efficiency and good throughput. TDMA-based scheduling proves to be one of the efficient methods but has problems of perfect time synchronization with increased network dynamics. The communication overheads in passing the handshake signal (RTS/CTS) are more, however, CSMA is suitable. The slot allocation for data transfer in multi-hop using CSMA prompts the surplus requirement of bandwidth as compared to TDMA [5-7]. To maintain a level of conflicts and bridge the network requirements with low and high traffic a hybrid CSMA/TDMA scheduling is proposed [9].

4.3. COLLISION AVOIDANCE MULTIPLE ACCESS TECHNIQUES

A channel access mechanism is used to regulate the radio of node for transfer of aggregated packets to sink. The different collision avoidance multiple access mechanisms are:

Time Division Multiple Access (TDMA): In TDMA, the data transfer from nodes to coordinating base station is organized into cycles with a number of fixed time slots. These slots are organized into frames and repeated for transfer of data. The disadvantage of TDMA is, it introduces the time drifts for low traffic loads reducing the throughput and increases the delay. It is best suited for dense networks for collision-free data communication with reduced energy consumption and an increase in throughput. The difficulty with TDMA mechanism is the synchronization of the nodes and adaptation to topology changes [5, 12].

Frequency Division Multiple Access (FDMA): FDMA is a channel access method used in multiple-access protocols as a channelization protocol. FDMA gives users an individual allocation of one or several frequency bands or channels. It coordinates access between multiple users with the requirement of additional circuitry and radio channels to communicate data. It consumes more energy which is scare in WSN [10].

Carrier Sense multiple access (CSMA): is a probabilistic Media Access Control (MAC) protocol in which a node verifies the absence of other traffic before transmitting on a shared transmission medium. It does not have the bandwidth and latency guarantee due to an asynchronous message passing mechanism. The technique is susceptible to variable traffic and is quite robust against interferences [25].

Code Division Multiple Access (CDMA): CDMA employs spread-spectrum technology and a special coding scheme (where each transmitter is assigned a code) to allow multiple users to be multiplexed over the same physical channel. CDMA can work as an efficient collision avoidance technique, only if its cost requirements are reduced [10].

4.4. MYOPIC AND NON-MYOPIC SCHEDULING FOR WSN

In this section, introduces the details regarding the implementation of bandwidth efficient scheduling algorithms, which considers the effects of stable, heterogeneous and mobile node and sink. The packets are scheduled according to the present and future state of the channel for maximizing the throughput that in turn correlates the bandwidth utilization [7, 9].

4.4.1. ASSUMPTIONS AND NETWORK MODEL

The assumption is that aggregation is permanent and messages that are aggregated will not split later. At each time slot, the process of transmission and aggregation is repeated until the sink (BS) collects all the messages. Clearly, aggregation will improve scheduling efficiency by reducing the number of packet transmissions and effectively conflicts. Consider that, if in-network aggregation is allowed, it can be done with a negligible cost of energy or computing power [5, 7-8]. If aggregation is not allowed, then one packet contains only one message and consumes more energy. The design assumptions include but are not limited to, placement of nodes, scheduling and synchronization strategies, states of the radio, mobility patterns and traffic models used.

Network Model

In the initial stage of the algorithm, all the nodes are deployed in the random manner and clusters are formed based on the clustering algorithm with metrics presented in [3]. A network is modeled as a clusters tree *T (V, E)* with CHs grouped into '*V*' set having '*E*' wireless links. The cluster tree is formed by many sub-trees T_1, T_2, T_3- T_n with '*n*' number of nodes in each cluster as shown in Figure 4-1 according to [7-8] is

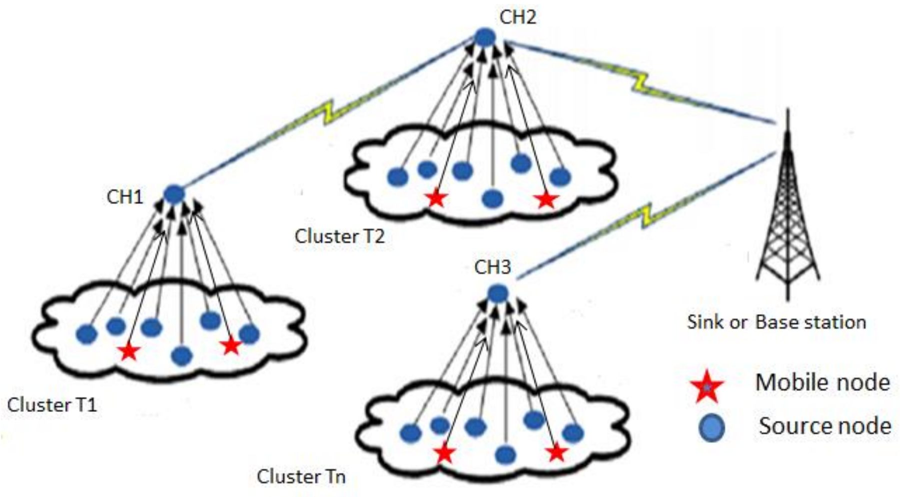


Figure 4- 1 Network model [7- 8]

The CH in each sub-tree aggregates 'm' number of messages from cluster members at time instant 't' using myopic scheduling and transfers to the next member in the path to sink. The multiple messages generated outside the first slot causes the collision and requires retransmission, which in turn increases the delay and energy waste. The algorithm recursively follows the steps utilized in intra and inter-cluster communication till aggregated message reach to sink [8]. The collision-free transmission is obtained by allocating the TDMA based scheduling slots for transmitting and receiving CHs in repeated form [7]. Each node in the network operates in the sleep and wake-up mode, which saves the energy. Also, the hop-by-hop transmission saves the energy with transmission cost as unit/per forwarding [5, 7-8].

4.4.2. PROPOSED MECHANISM

Problem of conflict-free slot allocation for the aggregated information and the scheduling decision in the cluster-based network with the stable and mobile state of sink and node is divided into two parts according to the concept in [7-8],

- In the first part (intra–cluster), myopic scheduling is used with consideration of the present state of the channel (i.e. communication between node and CH).
- In the second part (Inter-cluster), scheduling of slots depends on both present and future state of the available channel called non-myopic scheduling (i.e. for the CH --- CH to Sink).
- Node mobility is considered in the intra-cluster communication while the mobility of the sink is considered in the inter-cluster.
- The main aim is to improve the throughput (bandwidth utilization) with reduced energy consumption and delay.

The proposed structure of CMNMS mechanism is shown in Figure 4-2

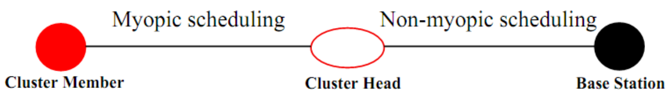


Figure 4- 2 Proposed mechanism of scheduling algorithms [7- 8]

Assume that all the individual node generates 'm' messages with weight '*Wm*' at the time instance t>0. All these messages are aggregated by CH as a set 'M'. Let 'S_t' be the schedule for the group of nodes to communicate the message during time slot 't' [7-8]. Then the system state of the static node used to perform the myopic, or non-myopic scheduling is represented as *fm(t)* with vector representation as *f(t)={fm(t)}* [7-8]. Also, the network has mobile nodes moving at 's' km/h speed, making frequent changes in the links and hence structure of the network *T (V, E)*. Therefore, during scheduling decisions, the mobility patterns are represented by a vector *f (t)s={fm(t)s}* at time 't' [8]. With mobility, 't_{mch}' denote the time when message 'm' arrives at CH, and 't_m' is the time required for scheduled message 'm' to reach the sink. If 'S' are the possible schedules for the represented state of the network, then the number of nodes $n \in S_t$ in the cluster will forward the message to CH with active links. The process repeats for message transmission from CH to the sink.

Energy Model

Nodes used in WSN are scare with energy, and most of their energy is consumed in communication, data transmission, reception, sensing, and deciding the schedule in a mobile environment. For the static condition of the node and sink, the energy model from chapter 2 section 2.5.3 is considered. The energy spent to transmit and receive an m-bits message over a distance *d*, called transmission distance and is denoted by $E_{tx}(d)$ and E_{rx} respectively [4] and is given by

$$E_{tx}(d) = m*(\varepsilon d^{\alpha} + E_{elec}), \text{ and } \quad E_{rx} = m* E_{elec} \qquad (4\text{-}1)$$

Where E_{elec} is the electronics energy, and 'ε' is the transmitter amplifier in the free space. For multipath model, 'α' is the path loss exponent, with $2 \leq \alpha \leq 4$.

We assume that a constant rate of energy drain will occur during node mobility. Let 'e_{move}' be the energy cost for the node and sink to move one unit distance and the distance traveled by the sink and node is *l*, then energy spent by the node and sink during their mobility [8, 26] is computed according to eq. (4-2),

$$E_{mv(l)} = e_{move} * l \qquad (4\text{-}2)$$

Delay Analysis for clustered network

The proposed network model uses the cluster tree with some clusters at each level. The scheduling algorithm considers the myopic and non-myopic scheduling of packets in the consecutive slots either in intra or inter-cluster communication [7]. The time required for 'N' nodes to schedule the 'k' packets in 't_{slot}'at CH is calculated according to eq.(4-3), and the time required for the number of CH with fewer collisions to sink is calculated by and to sink by eq.(4-4) according to concept [5, 7],

$$T_{ch} = ((N/k)-1)\, t_{slot} \qquad (4\text{-}3)$$

The total time required to send the aggregated response to sink is

$$T_{sink} = k.\, t_{slot} \qquad (4\text{-}4)$$

Hence, total time required for the aggregated packet to reach to sink from node is

$$T = T_{ch} + T_{sink} = [((N/k)-1) + k]\, t_{slot} \qquad (4\text{-}5)$$

All the activities of each node are scheduled and synchronized in the time slot $1 \leq t_{slot} \leq T$.

With controlled mobility of node and sink the time required to schedule the activity is increased and depends on the speed 's' of movement in [8] as

$$T = s * [((N/k)-1) + k] * t_{slot} \qquad (4\text{-}6)$$

4.5. RESULTS AND DISCUSSIONS

The parameters considered for simulation of CMNMS [7-8] are given in Table 4-1. The performance of CMNMS algorithm is compared with an efficient slot assignment algorithm GCF [15] and the cluster-based version of DRAND: A-DRAND [16], Both GCF and A-DRAND takes the decision of scheduling based on myopic scheduling.

Table 4- 1 Simulation parameters for scheduling algorithms [7-8]

Parameter	Value
Network area	100x100 meters
Number of nodes	25,50,75 and 100
Number of sources	24, 49, 74 and 99
Number of sinks	1
Initial placement of source and sink	Sources are placed randomly in the given area, and the sink (BS) is placed at the corner of the area. 100m*100m
Initial energy	100J
Propagation model	Two Ray- Ground
Traffic model	Constant bit rate
Idle power	14.4 mW
Receive power	12.06 mW
Transmit power	36.0mW
Runs of each simulation	20
Sink mobility/Node mobility	10/20 meters /sec

4.5.1. RESULTS WITH STATIC NODE AND SINK

In the initial part of the work, cluster based Myopic and Non-myopic algorithm (CMNS) [7] is developed for reducing conflicts occurred due to two-hop communication with increased throughput at the network with the static sink and nodes. Under this condition, once the nodes are randomly distributed, they are aligned with any one cluster, and CH is selected according to a number of the nearest node with one-hop connectivity and remaining energy (eq. 2-4). The scheduled function of intra-cluster communication *f(f(t),S) [7-8]*, is time dependant and represents the current state of the channel $f(t)$ with possible schedules 'S' available in time 't' is given by eq. (4-7),

$$f(f(t), S) = \sum_{m \in M} w_m \{f_m(t) \notin S, f_m(t) \neq V_{ch}\} \tag{4-7}$$

With non-myopic scheduling in inter-cluster communication, the scheduled function (*f(t)*, *S*) is the one step ahead of the current state of the channel availability at time t+1 and is given by eq. (4-8 and 4-9) [7-8],

For CH to CH communication,

$$f(f(t),[f(t),S]) = \sum_{m\in M} \underbrace{\{w_m\{f_m(t)\notin S,\ f_m(t)\neq V_{ch}\}\}}_{I} + \underbrace{\{w_m\{[f_m(t),S]\notin S,[f_m(t),S]\neq V_{ch}\}\}}_{II} \quad (4\text{-}8)$$

For CH to BS communication,

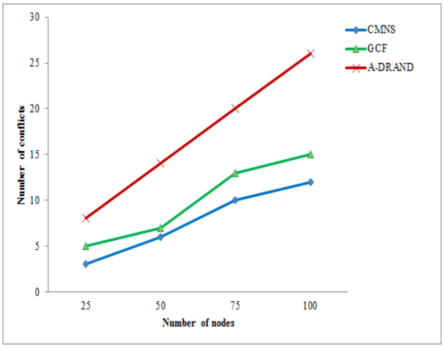
$$f(f(t),[f(t),S]) = \sum_{m\in M} \underbrace{\{w_m\{f_m(t)\notin S,\ f_m(t)\neq V_{bs}\}\}}_{I} + \underbrace{\{w_m\{[f_m(t),S]\notin S,[f_m(t),S]\neq V_{bs}\}\}}_{II} \quad (4\text{-}9)$$

In eq. (4-8) and (4-9), part-I and II works in a myopic and non-myopic way to reduces the collisions by allocating conflict-free scheduling slots[7-8].

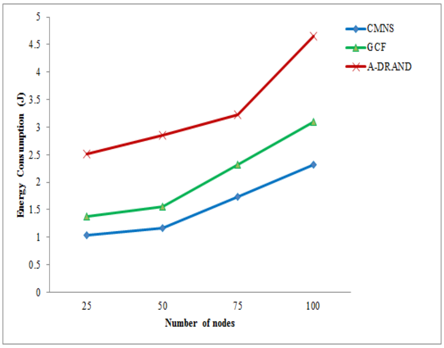
Number of Conflicts: In Figure 4-3(a), CMNS shows that conflicts in allocating the slots are reduced by 22.50% over GCF and 54.41% over A-DRAND. GCF and A-DRAND show more conflicts because they decide the schedule for transmission of packets on the basis of present state, while CMNS considered the present and predicted future state of channels availability. Also, GCF uses the three hop information and A-DRAND two-hop information for deciding the schedule in intra and inter-cluster communication.

Average Energy Consumption: It depends on the retransmission of the message causing collision in the channel due to improper allocation of the slot. In the case of CMNS, it is reduced by 25.06% and 52.09% over GCF and A-DRAND respectively as shown in Figure 4-3(b). This variation occurs due to the balancing of slot allocation according to available packets. The node will wake-up and sleep for forwarding the packets according to the present and predicted new state. On the other side, GCF and A-DRAND transfer messages in the present state of scheduling. Energy consumption in GCF increase since it decides the schedule based on three hop information with an increase in overheads. The mechanism used in CMNS helps to maintain less conflicts which lead in reduced average energy consumption.

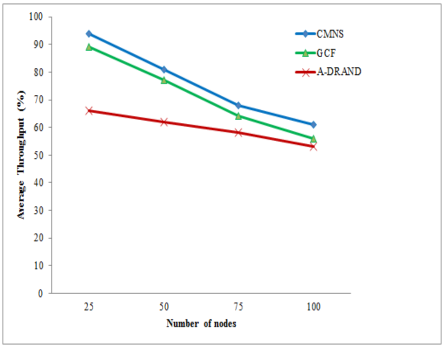
Average Throughput: Figure 4-3(c) CMNS has a better throughput of 6.29% and 27.19% over GCF and A-DRAND respectively. The reason for showing better throughput is the proper scheduling of conflict–free slots when nodes are active. This minimizes the retransmissions and saves the energy. Also, the used mechanism in CMNS reduce conflicts and leads to an increase in throughput.



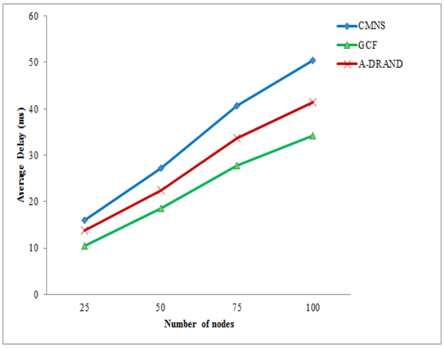
(a) Number of conflicts-CMNS



(b) Average energy consumption-CMNS



(c) Average throughput-CMNS



(d) Average delay-CMNS

Figure 4- 3 Results with static nodes and sink- CMNS [7]

Average Delay: The average delay depends on allocating the schedule to the packets for transmission either in intra or inter-cluster communication. It also depends on the decision based on the availability of the channel. Figure 4-3(d) shows CMNS has increased average delay as compared to GCF and A-DRAND due to the late decision of a predicted future state. The reason for reduced delay in A-DRAND is its adaptive nature to network traffic and transfers data immediately in the present state of the channel.

4.5.2. RESULTS WITH NODE MOBILITY [8]

The mobility of a node in the network affects the state of the channel since it makes frequent changes in the links. The results for SDNM [8] are obtained by considering the node mobility of 20 meters/sec. With increased node mobility, it is difficult to take the correct decision for scheduling the slots for transfer of aggregated packets. Consider that the node moves with speed‘s’ km/h with variation in the network structure *T(V, E),* with the state as *f (t) s*= {*fm (t)s*} [8]. The conflict-free schedule for message transmission from node to CH (V_{ch}) in a non-myopic way is given according to eq.(4-10 and 4-11) [8],

$$f(f(t)_s,[f(t)_s,S]) = \sum_{m\in M} \underbrace{\{w_m\{f_m(t)_s \notin S,\ f_m(t)_s \neq V_{ch}\}\}}_{I} + \underbrace{\{w_m\{[f_m(t)_s, S] \notin S, [f_m(t)_s, S] \neq V_{ch}\}\}}_{II} \tag{4-10}$$

Moreover, for CH to sink (V_{bs}) communication the channel state is

$$f(f(t)_s,[f(t)_s,S]) = \sum_{m\in M} \underbrace{\{w_m\{f_m(t)_s \notin S,\ f_m(t)_s \neq V_{bs}\}\}}_{I} + \underbrace{\{w_m\{[f_m(t)_s, S] \notin S, [f_m(t)_s, S] \neq V_{bs}\}\}}_{II} \tag{4-11}$$

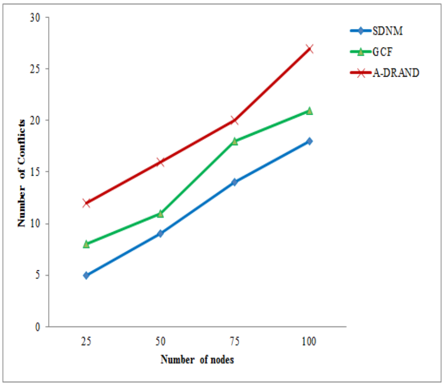
According to the ref [26] controlled mobility ensures the energy balance but with mobility may lead to degraded performance.

Number of Conflicts: With controlled node mobility in SDNM, the number of conflicts are reduced by 20.68% and 38.66% in comparison with GCF and A-DRAND as shown in Figure 4-4(a). Due to the mobility of nodes, collection and transmission of messages by predicting the future state is easy. SDNM balances the number of conflicts in intra and inter-cluster communication. The time taken by GCF and A-DRAND in making decision of available collision-free slot for transmission of messages at multihop increases causing collisions.

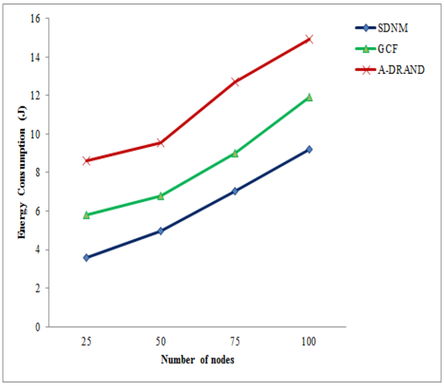
Average Energy Consumption: With the allocation of balanced collision-free slots for reduced conflicts, SDNM requires less energy to transfer the aggregated packets. It is reduced by 26.07% and 45.80% as compared to GCF and A-DRAND as seen from Figure 4-4(b). The reason for it is, mobile nodes comes in close proximity of cluster head and data collection at one hop requires less energy as compared to two and three-hop used by GCF and A-DRAND. The other reason is mobility of node inside the network changes the locations and has a number of possibilities in predicting the future state. Also, A-DRAND arbitrarily takes the decision of scheduling for transfer of packets in present state only and requires more energy. The SDNM prefers non- myopic scheduling in deciding the schedule that helps to maintain fewer conflicts.

Average Throughput: Figure 4-4(c) Throughput is actual count od packets reached to sink. SDNM has a better throughput of 6.80% as compared to GCF and 27.55% with A-DRAND. Collecting and transferring information from multi-hops in the present state of channel requires more time to find a conflict-free schedule, while A-DRAND takes a decision based on the randomized schedule. Controlled node mobility and collection of data from one hop source increases throughput in SDNM.

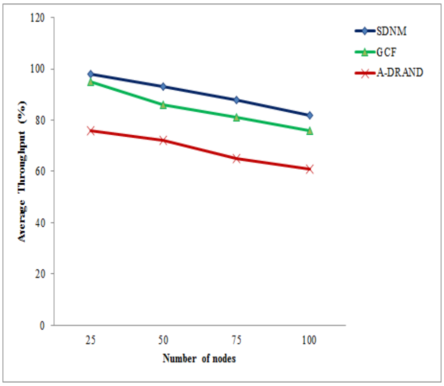
Average Delay: Figure 4-4(d) represents the corresponding result of average delay in allocating and finding the schedule. Due to mobility, location of the node changes and difficult to take decision without predicting future state and require more time. The reason for increased delay in A-DRAND is its adaptive nature to network traffic. SDNM shows 20.07% and 35.56 % improvement in the delay as compared with GCF and A-DRAND respectively [7-8].



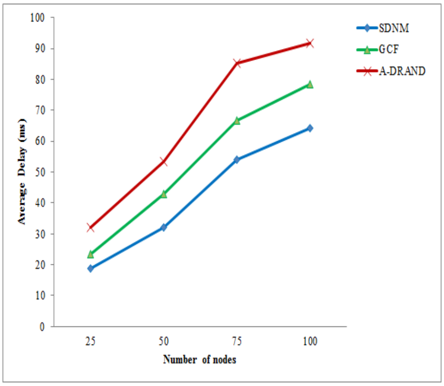
(a) Number of conflicts-SDNM



(b) Average Energy Consumption-SDNM



(c) Average throughput-SDNM



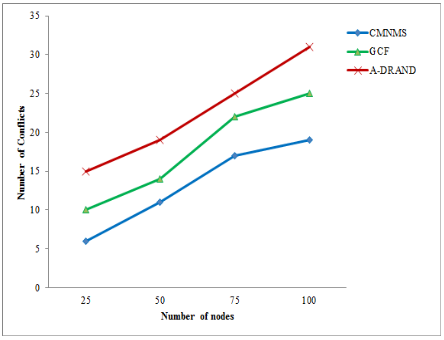
(d) Average delay-SDNM

Figure 4- 4 Results with node mobility- SDNM [8]

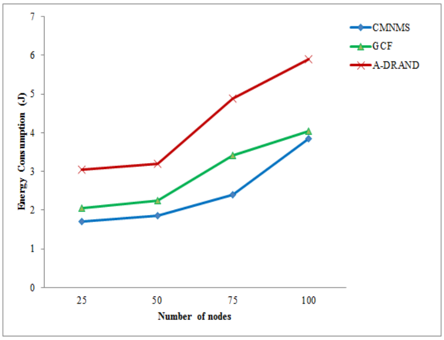
4.5.3. RESULTS WITH SINK MOBILITY

The performance of the scheduling algorithm is tested by adding mobility to sink for collecting the packets and is fixed at 10 mtrs /sec. The sink moves with the pre-defined path to collect the aggregated packets. The activities of the nodes are scheduled according to the availability of channel in either myopic or non-myopic way. It minimizes the time required to transfer the packets with one hop consideration and improves the utilization of channel with increased throughput.

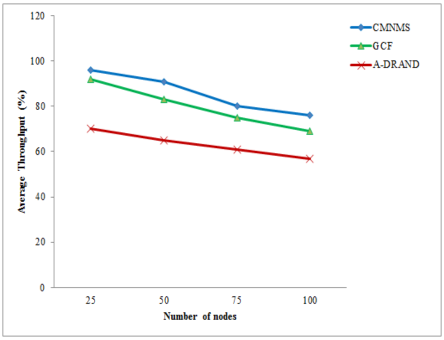
Number of conflicts: From Figure 4-5(a) the number of conflicts in the CMNMS algorithm are less by approximately 15% as compared to GCF and A-DRAND. It is due to mobility of a sink in the predefined path. The active node in the path will transfer the packets and due to scheduled wake up and sleep time possibility of false transmission is minimized.



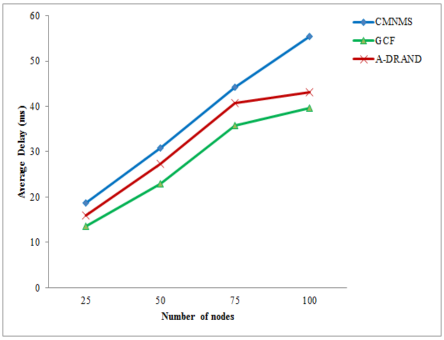
(a) *Number of conflicts-CMNMS*



(b) *Average energy consumption-CMNMS*



(c) Average throughput-CMNMS



(d) *Average delay-CMNMS*

Figure 4- 5 Results with sink mobility- CMNMS

Average Energy Consumption: According to Figure 4-5(b), with three scheduling algorithms, CMNMS algorithm has reduced average energy consumption by 16.62% and 42.43% than GCF and A-DRAND respectively. It is more than static sink (ref. Figure 4-3 b); the main reason is that it needs more control message to be exchanged between the nodes and position of the sink. The energy consumption in all cases is uniform till node density is 50 but increases after that exponentially in the case of CMNMS but random in GCF and A-DRAND, this is because of unstructured slot allocation with the movement of sink and data communication in multi-hops i.e.[Ec=

E1hop+ E2hop+ ----]. In GCF collecting information from three hops requires precise slot allocation for reduced energy consumption.

Average Throughput: Figure 4-5(c) shows the comparison of average throughput measured on the basis collision free packet transmission to sink. CMNMS has a better throughput of 7.52% and 35.57% over GCF and A-DRAND. It is due to the collection of more packets in the allocated time from the CH to mobile sink. The location information is communicated to sink in the initial stage of the traverse and sink travel according to a predefined path. Also, it is seen that as node density increases, the average throughput decreases. The node has to decide data transmission scheduled based on the present and future state of the channel, which changes with the movement of the sink. Most of the time in the myopic scheduling (present state) of the channel, links are direct and transfer packets without loss.

Average Delay: Figure 4-5(d) shows the average delay measured by the network when CH transmits the aggregated packets to sink. It is seen that average delay is more by 33.22% and 17.52% as compared to the GCF and A-DRAND, this causes because of predicting the future state in the inter-cluster communication and taking the next decision of schedule is complicated. The mobile sink continuously changes the position and is difficult to decide the schedule specifically in predicting the future state (non-myopic) and increase the amount of delay in the network.

From sections 4.5.1, 2 and 3, it is concluded that CMNMS performs better as compared to GCF and A-DRAND, but with the sink and node mobility, number of conflicts are reduced with an increase in throughput at the cost of increased delay. This causes due to finding the schedule of nodes with present state and predicting the future state of the channel. The increased throughput indicates the proper utilization of bandwidth.

4.6. SCHEDULE-BASED COLLISION AVOIDANCE ALGORITHM: SCA

In the low data rate applications using WSN, the transmission reliability and energy consumption plays an important role in the transmission of data and allocation of the conflict–free schedule for continuous operation. With the surge of packets due to the cooperative communication of the end nodes in WSN and requirement of sustainable operation of the network a Scheduled-based Collision Avoidance (SCA) [9] algorithm using ZigBee is proposed. The proposed SCA uses the activity-based sleep/ wake-up scheduling with duty cycle as computational metric. The combination of CSMA/CA and TDMA mechanisms for message passing and allocating the slot is used to find the trade-off between reliability and energy efficiency. The major reliability issue is due to collision of packets reaching to central coordinator through multiple paths at the same time [9, 27-28]. The performance is compared with synchronized, positional and channel-dependent scheduling algorithm resulting in an improved lifetime and reduced collisions.

4.6.1. SCHEDULING SCHEMES

The performance of multi-hop WSN, to accomplish high reliable data transfer, better throughput and reduced energy requirement depends on different scheduling techniques. The algorithms used for coordinated sleep/wake-up scheduling utilizes the network topology, traffic and duty cycle as the performance measurement tool and expressed in terms of communication period (CP) [9, 11, 29]. The different sleep/wake-up scheduling algorithms are characterized according to their functionality and defined in [9, 11] as:

Synchronized Sleep/Wake-up Scheduling: The sleep/wake-up schedule of all the nodes in the network is same and synchronized once at a time. It has high PDR and low energy consumption with TDMA as base scheduling technique [9].

Positional Sleep/Wake-up Scheduling: The sleep/wake-up schedule of node depends on the position and depth in the cluster-tree. It uses fixed duty cycle to manage the active period of each node and organized as a pipeline [9]. It has low PDR and increased energy consumption with CSMA as base scheduling technique.

Channel-Dependent Sleep/Wake-up Scheduling: The sleep/wake-up schedule of node depends on traffic and availability of channel. The active period is diverse for nodes at same depth in the routing tree i.e. adaptive duty cycle. It has low PDR and increased energy consumption with combination of CSMA and TDMA as base scheduling technique [9].

Activity-based Sleep/Wake-up Scheduling: The sleep/wake-up schedule of end node and parent depends on the activity. The single TDMA slot is allocated for the parent and child node to transfer the data. It has increased PDR and low energy consumption with combination of CSMA and TDMA as base scheduling technique [9].

4.6.2. PROPOSED NETWORK MODEL

The cluster–tree network model used by SCA [9] algorithm for obtaining reliable data transmission and energy conservation is shown in Figure 4-6. It consists of the ZigBee coordinator (ZC) or master node at address ‘0’ and manages all the activities of the network. The data from end nodes (ZCD), is aggregated at one node with respect to their relative position and depth in the routing tree and communicated to ZC through ZigBee routers (ZR). The required bandwidth for data communication is allocated dynamically by Guaranteed Time Slots (GTS) of super frame structure to reduce end-to-end delays and ZR buffer requirements. SCA is designed for the Personal Area Network (PAN) and uses IEEE 802.15.4 MAC [29].

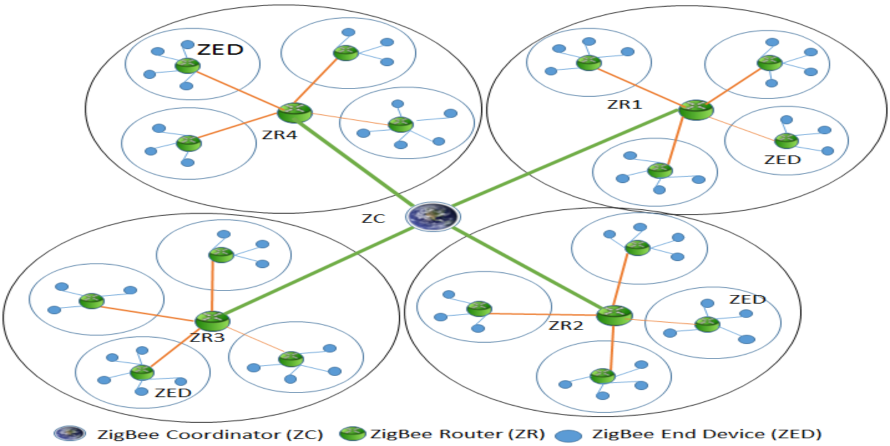


Figure 4- 6 Proposed network model- SCA [9]

Proposed Mechanism

SCA proposes a hybrid approach of CSMA and TDMA technique to avoid collisions with multi-hop communications [9]. It schedules the activities of parent and associated child nodes in the same slot by adjusting the duty cycle of each. All the packets are aggregated at single node before transferring to coordinator through router using the ZigBee-complaint super frame structure. Figure 4-7 is the proposed mechanism of SCA [9, 27], utilizes single parent and its associated children are active all together in same slot.

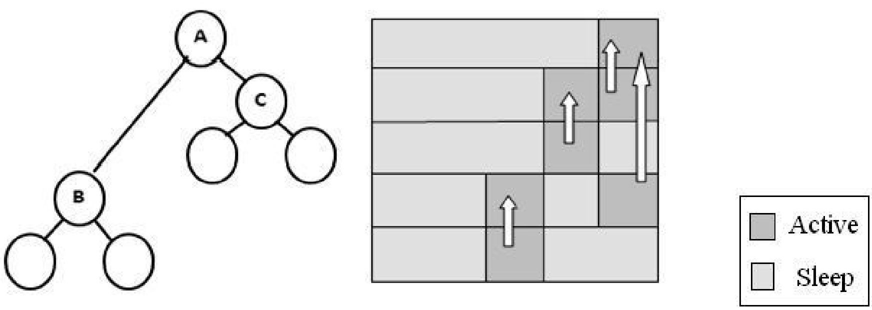


Figure 4- 7 Proposed mechanism- SCA [9,27]

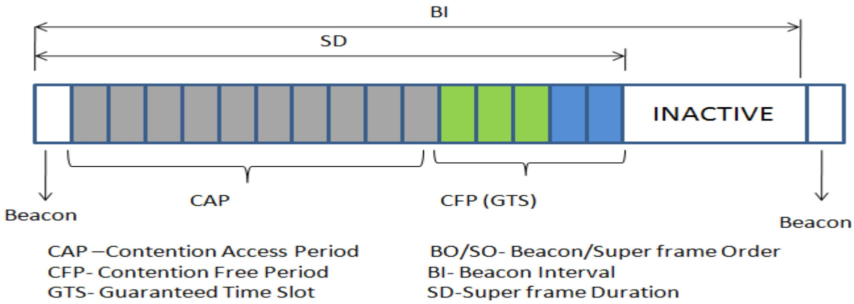


Figure 4- 8 Super frame structure- SCA [9]

The super frame structure used for providing the channel access and collision-free data transfer, is bounded by beacons is shown in Figure. 4-8 [9, 30-33]. The dynamic time frame for channel access and reliable data transfer is signified by the Super frame Duration (SD). The node competes for channel access in Contention Access Period (CAP) and transfers data using CSMA/CA scheduling technique. The Collision Free Period (CFP) is used for applications requiring low delay and reliable data transfer over channel. Both CAP and CFP are the part of SD and are used for energy management of the WSNs. By adjusting the sleep scheduling time of node the energy conservation can be achieved [9].

In a beacon-enabled mode, ZigBee coordinator synchronizes the nodes in PAN by sending the beacons periodically. The required power is managed by using the concept of duty-cycling and implemented through a super frame structure bounded by beacons shown in Figure 4-8 [9, 27, 33].

The main objective of SCA is to reduce the energy consumption and delay with improved PDR by application of activity based sleep/wake-up scheduling. TDMA scheduling provides collision-free slots to individual parent and child node for transfer of data packet. The control messages are transferred using CSMA techniques. The combination of TDMA and CSMA helps to reduce the energy consumption [9].

4.6.3. SCA ALGORITHM

The SCA algorithm [9] uses the beacon-enabled mode for slotted CSMA/CA scheduling mechanism for checking the channel access. For transfer of aggregated packets, the node has to check the availability of channel by performing the Clear Channel Assessment (CCA) test at the end of each back-off stage. The flow of SCA for reliable transmission of data packets with reduced energy consumption is drawn according to [9, 27, 33] and is shown in Figure 4-18.

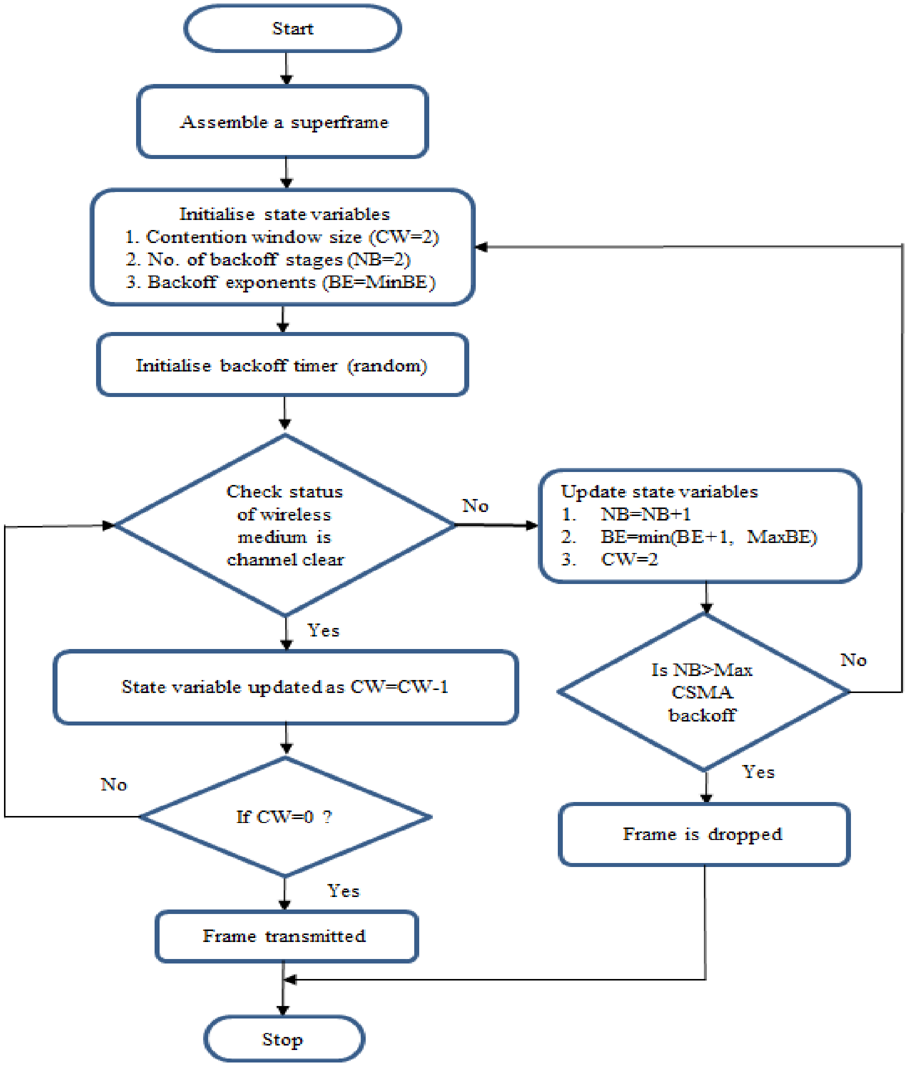


Figure 4- 9 Flow of SCA. [9, 27, 33]

4.6.4. RESULTS AND DISCUSSIONS

To improve the packet delivery ratio, throughput and delay with reduced energy consumption the network is simulated using NS-2 (ns-2.34) simulator. The other parameters used are according to ref [9, 34] and given in Table 4-2. ZigBee coordinator in the network activates the tree-addressing scheme. The scheduling mechanisms are working in the distributed manner where CSMA is used at the router level while TDMA at the coordinator to increase the throughput.

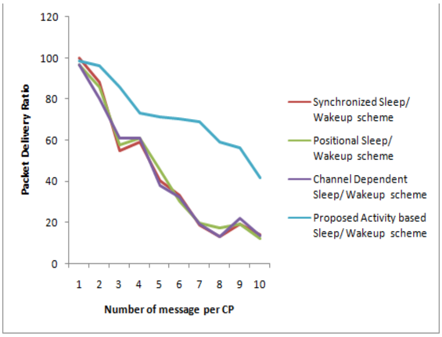
Table 4- 2 Simulation parameters of SCA [9]

Parameter	Value
Network area	100x100 meters
Number of nodes	81
Address and depth of ZC	0
Depth of network (Lm)	16
Number of children (Cm)	4
Number of routers	4
Transmission range	10 meters
Traffic model	Constant bit rate
MAC	IEEE 802.15.4
Computational metric	Duty cycle
Placement of node	Random
back off period for channel access	320 µs

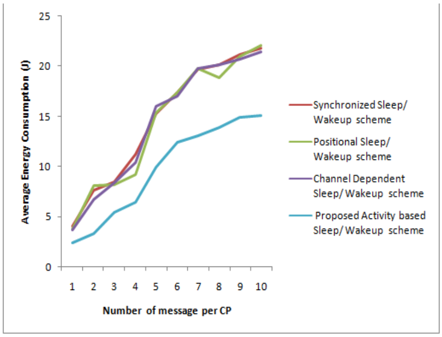
Packet Delivery Ratio: From Figure 4-10 (a) shows a trend of PDR with increased number of messages per frame. It is seen that, PDR of each scheduling scheme goes on decreasing with an increased number of messages. The synchronized scheduling has higher PDR than others in the initial stage due to even duty cycle and extends according to traffic. However, with an increase in the count of messages, proposed SCA shows increased PDR of approximately 64.34% as compared to synchronized, positional and channel-dependent scheduling. It is because of allocating the same TDMA slot for single parent and its associated child's, which avoids collision of packets.

Average Energy Consumption: In Figure 4-10 (b) proposed SCA shows reduced average energy consumption by 34.13% as compared to synchronized scheduling, and 32.45% & 32.98% with respect to positional and channel-dependent scheduling respectively. The activity-based scheduling performs better despite the fact that PDR is high and subtle to the message per frame (CP). SCA uses the decentralized approach where only one parent and its associated member nodes are active to transfer data packets to coordinator through router.

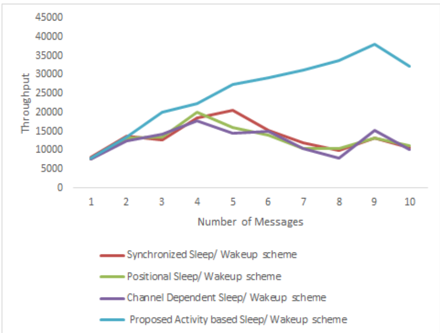
Throughput: Figure 4-10 (c) represents the comparison of throughput of scheduling mechanisms. The proposed activity based scheduling in SCA shows increased throughput of 47.33% as compared to synchronized sleep/wake-up scheduling, 19.38% with positional sleep/wake-up scheduling, and 51.09% compared with channel-dependent sleep wake-up scheduling. This improvement is due to variation in the duty cycle and balance of schedule between the ZigBee router and end nodes. In synchronized scheme, it is difficult to synchronize the local and global clock of nodes during scheduling of packets since all nodes use same sleep/wake-up time. The hierarchical structure in positional scheduling causes delay due to pipelining, while packets wait for the channel to free in channel dependent and causes the drop of packets. Throughput is the measure of the bandwidth consumed by the network.



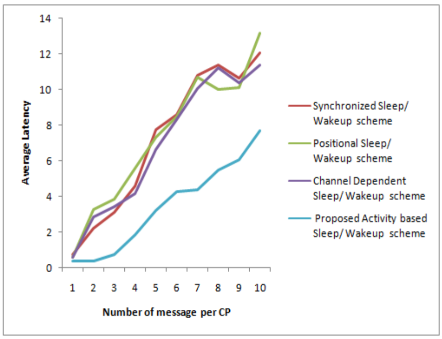
(a) Packet delivery ratio-SCA



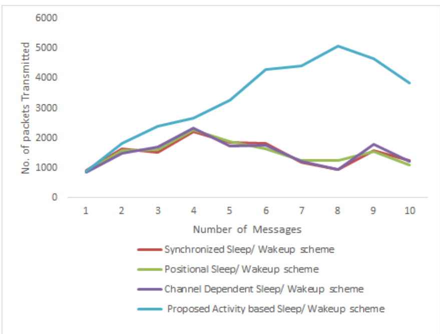
(b) Average energy consumption-SCA



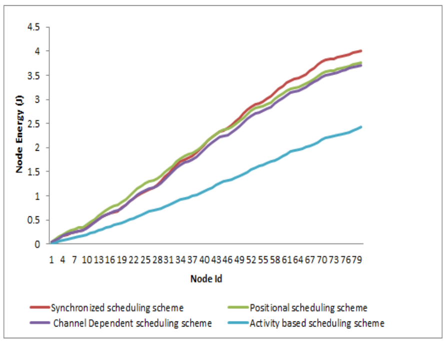
(c) Average throughput–SCA



(d) Average latency–SCA



(e) Number of packets transmitted–SCA



(f) Node energy variations–SCA

Figure 4-10 Results with scheduled collision avoidance algorithm- SCA [9]

Average Latency: It is the time taken by the child node to transfer packets to coordinator through router. Activity-based scheduling has reduced latency of 53% as compared to synchronized and positional wake-up scheduling, while 50.23% reduction in channel dependent as shown in Figure 4-10 (d). This is due to the queuing of the messages and variation in traffic at each parent during the active period.

Number of Packets Transmitted: From Figure 4-10 (e) the number of packets transmitted in SCA are increased by 9.35 % as compared with synchronized and 2% as compared with channel and positional sleep wake up scheduling. The packet dropout ratio is approximately 30% as compared with synchronized, positional and channel-dependent scheduling

Node Energy Variations: Figure 4-10 (f) demonstrates the node energy variations based on the duty cycle variations to transfer the packets. Node will wake-up only when event occurs along with parent node other, whereas it will be inactive. It saves the energy with increased lifetime of the network.

4.7. SUMMARY OF CHAPTER

This chapter gives comparative discussion with the major advantages and disadvantages of existing approaches, which gives the insight to develop new scheduling algorithms based on the myopic and non-myopic state of the channels. Algorithms are expedient for allocating the conflict–free scheduling slots based on the availability of channel and number of packets in the intra and inter-cluster communications. This chapter explores the four contributions: first, based on the static node and sink (CMNS algorithm), second is node mobility-based approach for minimizing the collisions of packets in the channel (SDNM, third based on the sink mobility (CMNMS). The hybrid approach used in CMNS [7] and SDNM [8] shows less number of conflicts, average energy consumption, and more throughputs as compared to GCF and A-DRAND. Under the static condition of the sink and node, the delay is less but increase with node mobility. With sink, mobility throughput is increased as compared with static and node mobility. In dense network myopic scheduling is preferred over non-myopic scheduling since allocation of conflict-free slots to CH and other backbone nodes for transfer of packets to sink is easy, which improves the channel utilization and throughput. Also, link scheduling with in-network aggregation is useful for reducing and analyzing the energy consumption and delay performance with increased throughput in case of a network with mobile nodes. The final contribution of chapter proposes a hybrid approach of CSMA and TDMA technique to avoid collisions with multi-hop communications [9]. With proposed activity-based scheduling PDR improves by 69.13% and 30% reduction in average energy consumption. The increased throughput with reduced packet dropout ratio indicates the utilization of channel bandwidth with the reliable transmission of packets.

4.8. REFERENCES

[1] B .Krishnamachari, “The Impact of Data Aggregation In Wireless Sensor Networks,” In the 22nd International Conference on Distributed Computing Systems Workshops (ICDCSW’02), Los Alamito, vol.1, pp.1-8, 2002.

[2] I.F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci,“Wireless sensor networks: a survey”, Journal of Computer Networks, 38(4), pp. 393–422, March 2002.

[3] Dnyaneshwar Mantri, Neeli R Prasad, and Ramjee Prasad, “Two Tier Cluster based Data Aggregation (TTCDA) in Wireless Sensor Network,” Springer Journal Wireless Personal Communications, 75(4), pp. 2589-2606, Nov. 2013.

[4] Dnyaneshwar Mantri, Neeli R Prasad, Ramjee Prasad, “Bandwidth Efficient Heterogeneity aware Cluster based Data Aggregation for Wireless Sensor Network,” Elsevier Journal of Computer and Electrical Engineering, vol.41, pp. 256–264, Jan 2015.

[5] Joo Changhee, Jin-Ghoo Choi, and N.B.Shroff, “Delay Performance of Scheduling with Data Aggregation in Wireless Sensor Networks,” IEEE Proceedings of INFOCOM 2010, 1(9), pp. 14-19, March 2010.

[6] Pei Huang, Li Xiao, S. Soltani, M.W. Mutka, and Ning Xi., “The evolution of mac protocols in wireless sensor networks: A survey,” Communications Surveys Tutorials, IEEE, 15(1),pp.101–120, 2013.

[7] Dnyaneshwar S. Mantri, Pranav Pawar, Neeli Rashmi Prasad, and Ramjee Prasad, “Cluster-based Myopic and Non-myopic Scheduling for Wireless Sensor Network,” 2014 IEEE Students' Technology Symposium (TechSym), pp.116-120, Feb.28-March2, 2014.

[8] Dnyaneshwar S. Mantri, Pranav Pawar, Neeli Rashmi Prasad, and Ramjee Prasad, “An Efficient Schedule based Data Aggregation using Node Mobility for Wireless Sensor Network,” Wireless Vitae 2013, pp.1-5, May 11-14, 2014.

[9] Dnyaneshwar Mantri, Neeli Rashmi Prasad, and Ramjee Prasad, “Scheduled Collision Avoidance in Wireless Sensor Network using Zigbee,” 3rd International Conference on Advances in Computing, Communications and Informatics (ICACCI2014), pp. 2129-2134, Sept. 2014.

[10] M Chitnis., P Pagano, G Lipari, and Yao Liang, “A Survey on Bandwidth Resource Allocation and Scheduling in Wireless Sensor Networks,”

International Conference on Network-Based Information Systems. NBIS '09, pp.121-128, Aug. 2009.

[11] Wu Yanwei, Li Xiang-Yang, Liu YunHao, and Lou Wei, “Energy-Efficient Wake-up Scheduling for Data Collection and Aggregation,” IEEE Transactions on parallel and distributed systems, 21(2), pp. 275-287, Feb. 2010.

[12] Mario Orne Díaz-Anadón,and Kin K. Leung, “TDMA scheduling for event-triggered data aggregation in irregular wireless sensor networks,” Computer Communication, 34(17), pp. 2072-2081, Nov. 2011.

[13] Hai Van Luu, Xueyan Tang, “An efficient algorithm for scheduling sensor data collection through multi-path routing structures,” Journal of Network and Computer Applications, vol 38, pp.150-162, Feb. 2014,

[14] Injong Rhee, Ajit Warrier, Min Jeongki, and Xu Lisong, “DRAND: Distributed Randomized TDMA Scheduling for Wireless Adhoc Network,” IEEE Transaction of Mobile Computing, 8(10), pp. 1384-1396, Oct. 2009.

[15] Pranav M. Pawar, Rasmus H. Nielsen, Neeli R. Prasad, Shingo Ohmori, and Ramjee Prasad, “GCF: Green Conflict Free Scheduling Algorithm for WSN,” ICC-E2Nets Workshop, pp. 5795-5799, June 2012.

[16] Shihan Li, Depei Qian, Yi Liu, and Jie Tong, “Adaptive Distributed Randomized TDMA Scheduling For Clustered Wireless Sensor Networks,” WiCOM, pp. 2688-2691, 2007

[17] Shrikant B,Harish M, and Bhattacharjee R, “An Energy Efficient Hybrid MAC Protocol for WSN containing Mobile Nodes,” International Conference on Information, Communication and Signal Processing (ICICS),pp.1-5, Dec 2011.

[18] F Mirian, and M. Sabaei, “A Delay and Accuracy Sensitive Data Aggregation Structure in Wireless Sensor Networks,” International Conference on Information Management and Engineering, (ICIME '09), 3(5), pp. 231-235, April 2009.

[19] Abdulaziz Y. Barnawi, “Adaptive TDMA Slot Assignment Using Request Aggregation in Wireless Sensor Networks,” The 3rd International Conference on Ambient Systems, Networks and Technologies (ANT), vol. 10, pp. 78-85, 2012.

[20] Mikhaylo K, Tervonen J, “Energy Consumption of the Mobile Wireless Sensor Network's Node with Controlled Mobility,” 27th International Conference on

Advanced Information Networking and Applications Workshops (WAINA), pp. 1582-1587, 2013.

[21] Nidal Nasser, Lutful Karim, and Tarik Taleb, "Dynamic Multilevel Priority Packet Scheduling Scheme for Wireless Sensor Network," IEEE Transaction on Wireless Communications, 12(4), pp. 1448 – 1459, April 2013.

[22] Sarma H K D, Kar A, Mall R,"Efficient routing protocol for wireless Sensor Networks with Node and Sink Mobility," 2011 IEEE Sensors Applications Symposium(SAS), pp. 239-243, 2011.

[23] Chi-Tsun Cheng, and Tse C.K., "A Delay-Aware Network Structure for Wireless Sensor Networks With Consecutive Data Collection processes," Sensors Journal, IEEE, 13(6), pp. 2413-2422, June 2013.

[24] Stevan Marinkovic, Christian Spagnol, and Emanuel Popovici, "Energy-Efficient TDMA-based MAC Protocol for Wireless Body Area Networks," Third International Conference on Sensor Technologies and Applications, 2009 (SENSORCOMM '09), pp. 604-609, June 2009.

[25] Himanshu Singh, & Bhaskar Biswas, "Comparison of CSMA-Based MAC Protocols for Wireless Sensor Networks," International Journal on AdHoc Networking Systems (IJANS), 2(2), pp.1-10, 2012.

[26] Zeydin Pala Kemal Bicakci, and Mustafa Turk, "Effects of node mobility on energy balancing in wirelessNetworks," Computers and Electrical Engineering vol.41. pp. 314–324, 2015.

[27] Giuseppe Anastasi, M Conti, M Di Francesco, and V. Neri, "Reliability and energy efficiency in multi-hop IEEE 802.15.4/ZigBee Wireless Sensor Networks," IEEE Symposium on Computers and Communications (ISCC), pp. 336-341, 2010.

[28] Mario Di Francesco, Giuseppe Anastasi, and Marco Conti, "Reliability and Energy-efficiency in IEEE 802.15.4/ZigBee Sensor Networks: An Adaptive and Cross-layer Approach," IEEE Journal on Selected Areas in Communications, 29(8), pp. 1508-1524, Sept. 2011.

[29] Hanzalek Z.,and Jurcik, P., "Energy-Efficient Scheduling for Cluster-Tree Wireless Sensor Networks With Time-Bounded Data Flows: Application to IEEE 802.15.4/ZigBee," IEEE Transactions on Industrial Informatics, 6(3), pp.438-450, Aug. 2010.

[30] Chi-Ming Wong, "A novel beacon frame scheduling algorithm based on cluster-tree IEEE 802.15.4 wireless sensor networks," 2012 IEEE International Conference on Communication Systems (ICCS), pp. 285-289, Nov. 2012.

[31] Qiong Liu, and Czylwik A, "A collision-aware backoff mechanism for IEEE 802.15.4 wireless sensor networks," Wireless Days (WD), 2013 IFIP, pp.1-3, Nov. 13-15, 2013.

[32] Chang Yong Jung, Ho Young Hwang, Dan Keun Sung, & Gang Uk Hwang "Enhanced Markov Chain Model and Throughput Analysis of the Slotted CSMA/CA for IEEE 802.15.4 Under Unsaturated Traffic Conditions," IEEE Transactions On Vehicular Technology, 58(1), pp. 473-478, 2009.

[33] Chiara Buratti, and Roberto Verdone, "Performance Analysis of IEEE 802.15.4 NonBeacon-Enabled Mode," IEEE Transactions on Vehicular Technology, 58(7), pp. 3480-3493, Sept. 2009.

[34] André Ribeiro e Cunha "On the use of IEEE 802.15.4/ZigBee as federating communication protocols for Wireless Sensor Networks" July 2007.

CHAPTER 5. SYNCHRONIZATION ALGORITHMS FOR BANDWIDTH UTILIZATION IN WSN

The chapter illustrates hierarchical structure used to develop the synchronization algorithm for efficient utilization of bandwidth. The proposed synchronization algorithms consider the system model based on clustered spanning tree mechanism which works on level-by-level synchronization. The activities of the node are scheduled and synchronized with the notion of the global clock for reducing the clock skews. The chapter surveys the different synchronization mechanisms and proposes hybrid synchronization mechanism (scheduling + synchronization) for obtaining the improved performance as compared with existing state-of-the-art solutions. The reduced synchronization errors energy consumption, delay along with improved throughput are the performance measures. The effectiveness of the algorithm is verified with different scenarios as static, mobile and heterogeneous nodes in the network.

5.1. INTRODUCTION

WSNs have received considerable attention in collection and transmission of reliable data in inevitable potential applications. The primary challenge in synchronized data aggregation and communication of packets to the sink for increased throughput is to schedule and synchronize the activities of the nodes with global clock [1-2]. For instance, if nodes used for sensing and collection of data are provided with diverse scheduling slots and not synchronized with the common time scale, then the result will be distinctive and uneven. To have coordinated operation with a minimum number of conflicts in slot allocation and transmission, local clock of nodes must be synchronized with sink- a global clock. Also, to avoid the collisions and reduce the energy consumption with increased throughput, slots must be synchronized with a global timescale for communicating the aggregated packets to sink. Since the clocks used for time stamping in node operate independently and, may not be synchronized with each other.The unsynchronized nodes face difficulty in integrating and interpreting the information sensed by the nodes [10-11]. Likewise, topological variations caused due to mobility and scarce resource of nodes as bandwidth restricts the multi-hopping and demands for new solution differing from traditional ones having the capability of estimating the time uncertainties accurately.

Timing-Synch Protocol for Sensor Networks (TPSN) [3], considers the hierarchical structure and performs pair-wise synchronization for the two-way message exchange between sender-receivers with global time scale of the network. The time synchronization in WSN is indispensable due to infrastructure-less network and consumes more energy with increases retransmission delay in communication. To avoid collisions and re-transmission of discarded packets a balanced approach of scheduling and synchronization is required from the lower layer to the upper layer. The comparative analysis of different synchronization strategies for WSN are presented in [4]. To achieve the efficient utilization of scarce resources of the node an efficient schedule based MAC for managing the time slots node and CH along with time stamping is required. For instance, the scheduling protocol such as TDMA used in the network strictly demands synchronization among nodes. Besides, low-cost clocks and resource constraints nodes, the time and clock synchronization in the WSN is affected by communication errors caused due to drift, frequent topological changes, node failures and clock drifts [5, 10, 16].The node and network-wide synchronization from root node to parent avoids the disparity of packets used for communication. To get better results in the WSN networks with clock synchronization, a layered cluster-tree is preferred for one-hop or multi-hop data proliferation from node to CH and CH to the Sink as spanning tree (SPT) mechanism [6]. "*The tree-structured synchronization protocols are suitable for sensor networks with few nodes while distributed for the large sensor network. Synchronization algorithms co-ordinate the time scale of node and network, and scheduling algorithms allocate the collision-free time slots to reduce the energy consumptions, delay and increase in throughput* [7-12]".

The chapter proposes hybrid synchronization algorithms to establish the hierarchical structure of network using cluster-based spanning tree to address the issues in the synchronization and improve them in the presence of non-ideal clocks. The chapter has three-fold contribution based on static, mobile and heterogeneous nodes and addresses the challenges of synchronization. The Synchronized Data Aggregation Algorithm (SDA) [10] uses the static nodes for the formation of clustered network. The proposed working mechanism uses SPT for obtaining the results than the structured network. The level-by-level synchronization of nodes with a global time scale of network shows improvement in performance parameters. Bandwidth Efficient Hybrid Synchronized Data Aggregation Algorithm (BESDA) [11] considers the mobile nodes with static sink. The energy consumption of network increases with the addition of mobile nodes due to frequent changes in the network dynamics. It is also difficult to coordinate the activities of nodes with the global time scale. To overcome the glitch, the data aggregation in BESDA is carried out with global-time scale through out the network, while slots are synchronized to minimize the conflicts increasing throughput. The work is extended by developing the hybrid (scheduling and synchronization) synchronization algorithms based on random mobility and heterogeneity of node as Mobility-aware Hybrid synchronization (MHS) [12] and Node Heterogeneity for Energy Efficient Synchronization (NHES) [13] and Heterogeneity–aware Bandwidth Efficient Hybrid Synchronization [14] for improving the energy efficiency and bandwidth utilization.

5.2. RELATED WORKS

To achieve better energy saving, increased throughput and reduced synchronization errors and clock skews occurring due to mismatch of synchronized scheduling slots with respect to the global clock of the network, this section explores the different possibilities, methods and techniques used in scheduling (TDMA) the slots and synchronization techniques to improve the QoS. [5] Considers the CH as a source of reference clock than root nodes. During the failure of root node the system clock is adjusted according to the time. [6] Uses the spanning tree mechanism to synchronize the sub-trees in the network with level-by-level. The sub-tree synchronization process helps to match the clock time within the level. It minimizes the clock adjustment time.

In [7], the proposed data aggregation tree collets the data from multiple points on the basis of time drift and phase offset of nodes. The time synchronization is obtained during formation of aggregation tree.

In [8], energy saving is achieved by allocating the conflict-free slots to mobile nodes. The aggregated packets are transferred in consecutive time slots using TDMA as basic MAC. In [9], different schemes of scheduling are presented for effective data gathering and processing. Slots are allocated on the basis of data rates received from nodes. The proposed consecutive slot assignment TDMA-MAC reduces the state transitions conserving energy. "*The TDMA based schemes have problems of perfect time synchronization, and not suitable for scalable network due to the high network planning overhead* [10-11]".

In [10], energy consumption and sync errors are reduced using level-by-level synchronization of nodes with a parent. The data is aggregated using spanning tree mechanism at the notion of global time scale. [11-14] proposes the hybrid approach based on the node mobility and heterogeneity to improve the bandwidth utilization. In [15], reduced packet delay and high throughput is obtained by scheduling the communication in clustered network using Cycle-based synchronous scheduling. The optimized cycle length and transmission order along with clustering is best suited for WSN used in delay–sensitive applications. External Gradient Time Synchronization Protocol (EGsync) [16] addresses the issue of external node synchronization with reference node by optimizing the clock skews from neighboring nodes. EGsync incurs computational and communication overloads while providing tight synchronization.

Reference Broadcast Synchronization Protocol [17] (RBS) uses the synchronization between two receivers by the intermediate node within the listening range of sender and receiver. The intermediate node sends the message for recording the time, hence saves the energy in clock updates. The energy required in synchronizing the reference sender in RBS is high. The adaptive value tracking Time synchronization protocol is presented in [18] to reduce the computational and communication overheads through successive feedbacks. The speed of operation is increased by adjusting the offset of the rate-synchronized clock without the need of network-wide synchronization. Algorithm presented in [19] for data aggregation considers the communication and delay costs using synchronous and asynchronous time model. The algorithm has time complexity in switching from modes with small clock drifts and balanced data aggregation.

Clustered Time Synchronization algorithm (CTS) [20] presents the level-by-level synchronization of CH and nodes with the global clock. It saves the energy required to communicate the messages beside accuracy. [21] Proposes the hybrid scheme to ensure the sync accuracy with minimum energy. It considers partial scheme to calculate the time offset of few child nodes. Green Conflict Free (GCF) [22] considers the conflict graph to achieve better slot sharing and reuses of slots. It improves the scalability and energy efficiency by finding the conflict-free TDMA scheduling slots for the three hop neighbors to transfer the message and reduce collisions. In Adaptive DRAND (A-DRAND) [23] with increased node density it difficult to maintain the energy balance in the network. For collision-free data transfer CH is assigned more slots, while other members alter the role of CH after specified time interval to balance the energy. This reassignment of slots increases the overheads. [24] Introduces the concept of single and multiple movable data collectors along with space division multiple accesses techniques. It minimizes the routing and data gathering by time optimizing, while multiple collectors are distributed according to regions increasing data gathering time. According to [25] the controlled mobility of nodes in the network with real life examples, helps to conserve energy in data gathering from one hop node. Also, the group mobility model for nodes with cluster-based data aggregation is presented in [26] which considers distance and probability. The topology of the network changes with mobility and requires more time to take decisions hence not suitable to SPT mechanism for improved data aggregation accuracy.

According to the literature survey, the synchronization algorithms used for energy efficient bandwidth utilization have challenges as scalability to network changes with an increase in node density, self-configuration, robustness, synchronization of the local and global clock, minimize clock drifts, minimize synchronization overheads, and the communication range of the mobile nodes. This chapter addresses few of them for reducing the synchronization errors, energy consumption, delay and increase in throughput.

5.3. SYNCHRONIZATION CONTROL ALGORITHMS FOR WSN

The section gives details regarding the implementation of bandwidth efficient hybrid synchronization algorithms, which considers network with static, mobile and heterogeneous nodes and sink. To minimize the clock skew and synchronization error, the clock of the node is synchronized with global time-scale and clock of the network [10-14]. The cluster-based spanning tree with level-by-level synchronization reduces the energy consumption with improvement in throughput.

5.3.1. NODE AND NETWORK ASSUMPTIONS

The node and network assumptions of the algorithms used in this chapter are considered from section 2.4.1 and 3.3.1 except- Parent node (CH) broadcast the reference time, all nodes synchronize their time with a global time of the network. The sink is equipped with GPS capabilities, communication between the CH and member node is one-hop [10].

5.3.2. NETWORK MODEL

"*Consider a network tree T (V, E), where 'V' denotes the set of 'n' wireless nodes and 'E' denotes the set of wireless links developed by the static, mobile and heterogeneous nodes as shown in Figure 5-1 (extension of Figure 2-3). The network T (V, E) is divided into many sub-trees T_1, T_2, T_3... Tn called as a cluster*" Ref. (Section 4.4.1, Figure 4-1) [8, 10].

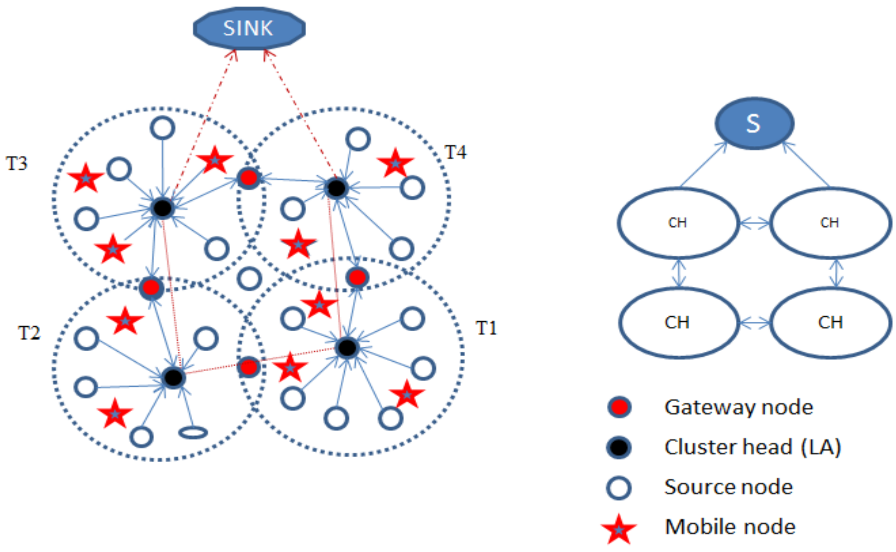


Figure 5- 1 Network model [11-14]

Every sub-tree has one CH, which act as root for each node to transfer aggregated data packets to sink. The sink is located at the root and maintains the global time-scale to synchronize the CH and nodes at different layers of tree. This reduces transmission time per forwarding [10]. The aggregated packets are scheduled with time slotted MAC [8] and forward in the error-free channel by synchronizing the slots (t_{slot}) and local clock of node with the reference clock of the network [10-14]. *"In the initial stage of the algorithm, the message 'm' generated in the time interval 't_m' is aggregated with time stamp at CH (parent in the tree)[10-11]*" In the second level, the collision-free packet transmission to sink is done by allocating the TDMA–based schedule to all the CHs [11].

5.3.3. PROPOSED MECHANISM

The proposed hybrid (scheduling + synchronization) synchronization utilizes spanning tree mechanism to reduce the clock skews and synchronization error. The clock synchronization of nodes at a depth of tree and network is done according to level-by-level approach. It reduces the overall energy required for broadcasting the message and improves throughput [10-14]. The hybrid synchronization algorithm is developed according to the steps as.

1. Form the cluster-based spanning tree and perform level-by-level aggregation.
2. Schedule the activities of nodes and CHs according to free slots to reduce the collision of packets.
3. Synchronize the slots and clock of the node with the reference node in the network to reduce energy consumption.
4. Reduce the errors occurred due to clock skew, hence the energy consumption and delay.
5. Improve the throughput (bandwidth utilization) using a hybrid approach (Scheduling + Synchronization).

Formation of Spanning Tree [6, 11, 20]

In the proposed hybrid approach of synchronization, the Kruskal algorithm is used to form the minimum SPT of graph *G (V, E)*. The randomly distributed nodes are first aligned into clusters according to the node clustering algorithm specified in [8]. In the second half, the CH is assigned address 0 and the nodes at the one-hop weight and receiving broadcast message of CH are added into the forest to form spanning tree inside the cluster (intra-cluster SPT) [10-14]. The address of the member nodes inside the cluster goes on changing according to the depth of tree and synchronized level-by-level. With the addition of mobile nodes some loops are formed and edges forming loop are discarded. The network wised spanning tree recursively uses the same algorithm used in the individual cluster. In the inter-cluster SPT Sink is assigned with address 0 and CH receiving the broadcast message are added in group to transfer the packets received from lower layers as shown in Figure 5-2. [10-14, 20].

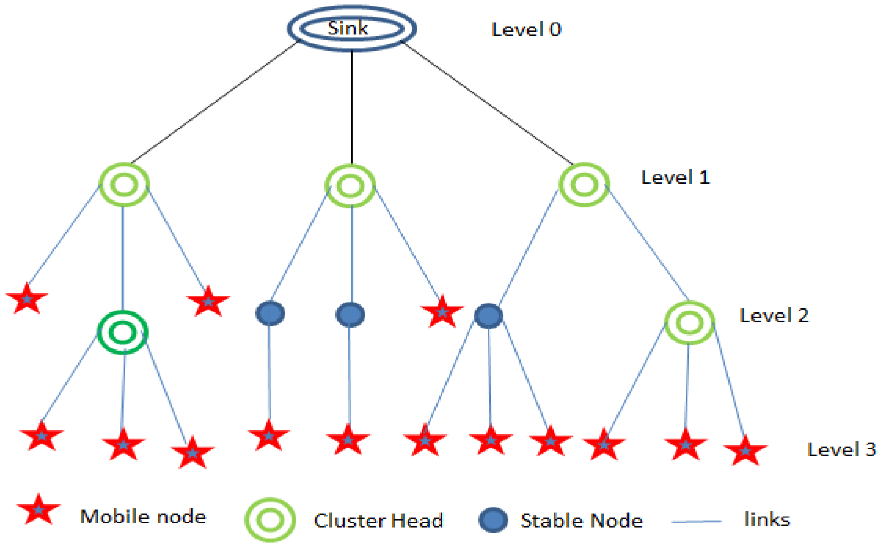


Figure 5- 2 Spanning tree mechanism [10-14,20]

Node Synchronization in SPT

In the SPT mechanism, node at lower layer are synchronized with parent node level-by-level. In the network level synchronization by default sink will be at level 0, all CH at level 1 and nodes inside the cluster at level 3 and so on i.e Sink-CH-Nodes. The sink node maintains the global notion of time [10-11]. The clock estimation of sink for transfer of data is obtained as :

In the synchronization mechanism, the total time required for reception (T2) of synchronization packet from nodes A to B is given by eq. (5-1). [3, 14]. It is the composition of transmitter time (T1), propagation delay (d) and the clock drift between the two nodes (Δ),

$$T2 = T1 + \Delta + d \qquad (5\text{-}1)$$

The total propagation delay and clock drift depend on the acknowledge time (T3) of receiver node 'B', and time T4 'A' receives an acknowledgment packet from 'B'. Then according to transmission, reception and acknowledge time T1, T2, T3, and T4 the drift and delay is calculated using eq.(5-2 and 5-3):[3, 14]

$$\Delta = (T\,2 - T\,1) - (T\,4 - T\,3) \qquad (5\text{-}2)$$

$$d = (T2 - T1) + (T4 - T3) \tag{5-3}$$

The transmitter node 'A' can correct its clock by knowing the drift, and then it synchronizes to node B. Root node initiates time sync packet and receiver node Rx wait for random time to avoid contention before two-way message exchange between a pair of nodes. If the node is not assigned with level, it sends a level request message and its close neighbor reply with its level to update called local discovery. If acknowledgment to the sender is not received it, retransmit synchronization packet. If acknowledge is not received even after three retransmissions, then root node sends level request message once again. In this way, all the nodes in the level and network are synchronized. The level-by-level mechanism reduces the overheads [10-14].

Slot Scheduling

The conflict-free scheduling algorithms [8, 9] are used to allocates the slot for transfer of aggregated packets from the node. It uses TDMA as basic MAC, for taking the decision on the basis of present and predicted future state of the channel.

Energy and Delay Analysis

In WSN, most of the node energy is consumed in the process of communication. Typically, depending on the state of the nodes radio either in transmitting, in listing or sleep mode, energy consumption is decided. It also depends on packet transmission rate and distance of node in the respective level with respect to parent. According to [12-14] the level of nodes in the SPT, the energy consumption is,

$$e(di) = k(e_t\, di^{\alpha} + e_0)\, t_{slots} \tag{5-4}$$

α- path loss and depends on the distance of a node to CH and sink, k- Number of packets, e_t- transmitter energy, e_0- initial energy.

The main objective of the hybrid approach used in synchronization algorithm is to increase the throughput of the network with minimum energy consumption. The radio states have different energy consumption (energy consumption per unit time) as a transmitter (E_{tx}), receiver (E_{rcv}), listen (E_{lst}), and sleep (E_{slp}), respectively. We assume that the total time is logically divided into slots as t_{slot}, and time slots are synchronized among nodes. A scheduled period 'T' is composed of consecutive time slots as shown in Figure 5-3.

Assume that a node n_i will produce r_i data packets per scheduling period T. Thus, in the one-time slot, a node can transmit multiple data packets under the ideal environment. When a node n_i is transmitting packets to a neighboring node n_j with in intra-cluster, some other neighboring nodes that are in the listening state will also transmit its available data packet and consume energy.

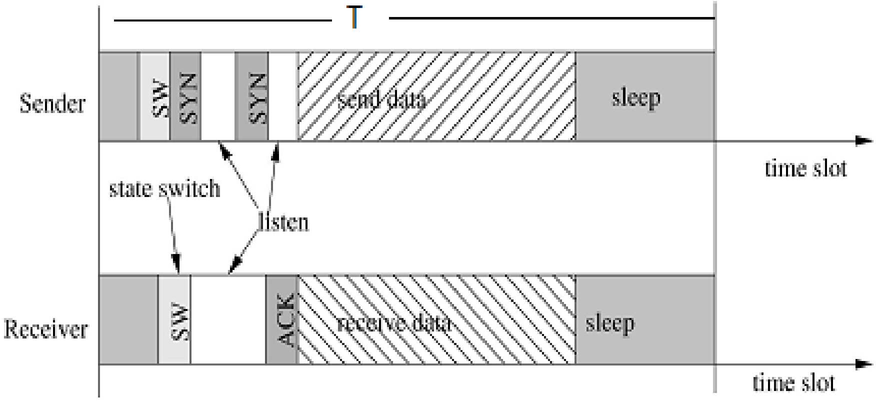


Figure 5- 3 Synchronization frame [12-14]

Therefore, the total energy consumption of node ni that transmits the data packets in L slots listening to neighboring nodes is given by eq.(5-5) according to [12],

Energy consumption= $(E_{tx} + E_{rcv} + n * E_{lst}) L * t_{slot}$. (5-5)

Also, the time required to schedule the 'k' packets at CH and then to sink is calculated according to the number of forwarding's [12-14] and is given by eq.(5-6) (Ref section 4.4.2):

$$T = [((N/K)-1) + K] t_{slot} \quad (5\text{-}6)$$

All the activities of each node are scheduled and synchronized in the time slot $1 \leq t_{slot} \leq T$.

5.4. RESULTS AND DISCUSSIONS

The performance of proposed synchronization algorithms are analyzed using NS-2 (ns-2.34) network simulator and parameters used are summarized into Table 5-1. The SPT mechanism is used to obtain results in the clustered-tree network consisting of static, mobile and heterogeneous nodes. The performance of hybrid synchronization algorithm is compared with time synchronization (TPSN) [3] and also applied on GCF [22] and A-DRAND [23] as a scheduling algorithm. The synchronization mechanisms are used to reduce the clock skews and errors, which in turn increase the throughput. The hybrid algorithms are proposed which takes care of synchronizing the clocks of nodes with the global clock of network and synchronized packets are scheduled in the channel to minimize the conflict and improve the QoS parameters.

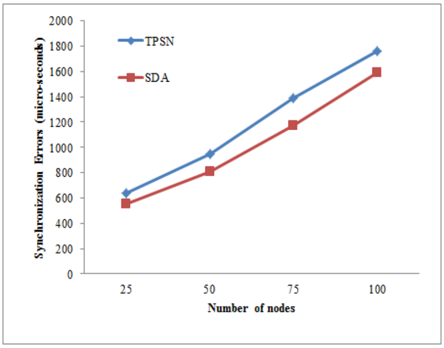
Table 5- 1 Simulation parameters- synchronization algorithms [10-14]

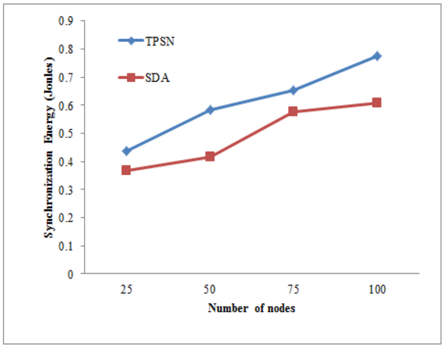
Parameters	Value
Network diameter	100x100 meters
Number of nodes	25,50,75 and 100
Number of sources	24, 49, 74 and 99
Number of sink	1
Type of nodes	Static, Mobile and Heterogeneous.
Placement of source and sink	Random and sink at root
Initial energy	100J
Propagation model	Two ray ground
Traffic model	Constant bit rate
Idle power	14.4 mW
Receive power	12.06 mW
Transmit power	36.0mW
Node Mobility	20 meters/sec
Mobility model	Random waypoint [28]
Runs of each simulation	20

5.4.1. RESULTS WITH STATIC SINK AND NODE: SDA

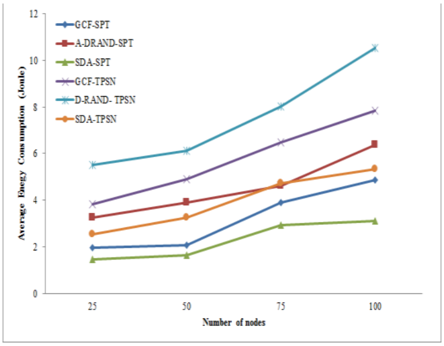
The network used for SDA [10] if formed using static nodes and sink. The nodes are randomly placed and are organized into the clusters. Nodes in the cluster and clusters in the network form the spanning tree to communicate the aggregate packets from the leaf node to root (sink) [10]. The nodes in the intra-cluster are synchronized with the clock of CH and CHs in inter-cluster with a clock from the root node. Such level-by-level synchronization helps to minimize the clock skew which in turn reduces the synchronization errors and required energy.

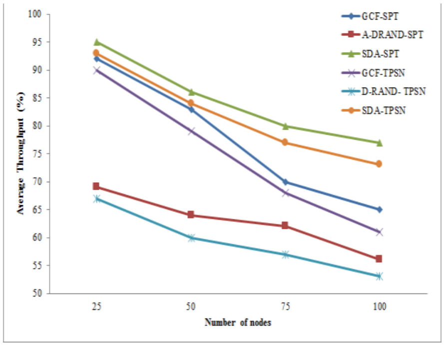
Synchronization errors and energy consumption: The basic problem with the distributed WSN is that the energy waste is increased due to increased clock skew and improper balancing of node and network clock. From Figures 5-4(a) and 5-4(b) The proposed, SDA [10] algorithm shows better performance in case of SPT mechanism than TPSN, since TPSN uses global time scale for all nodes to synchronize. Also, TPSN has added uncertainty at the sender end causing errors and requires more energy.



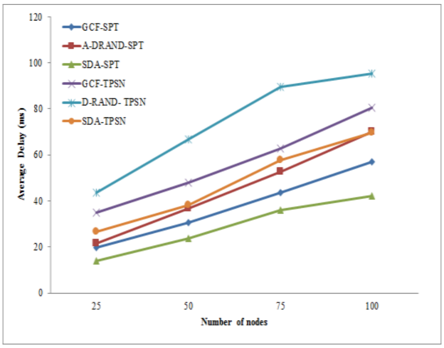


(a) Synchronization error-SDA *(b) Synchronization energy-SDA*





(c)Energy consumption-SDA *(d)Throughput-SDA*



(e) Delay-SDA

Figure 5- 4 Results with static node and sink- SDA [10]

In the proposed synchronization algorithms, the scheduling slots are synchronized to transfer the packets and every node is synchronized with global time maintained by the sink. It performance level-by-level synchronization reducing the overheads required in synchronizing the lower layer node with sink hence shows reduced errors of 9.86% and energy consumption of 21.49% as compared to TPSN. The process of synchronizing the clocks within the level with reference node minimizes the transfer of messages and reduces the error.

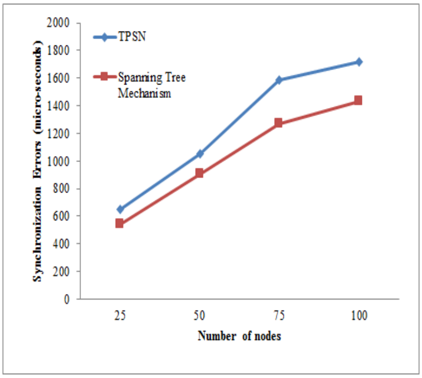
Average Energy Consumption: With the application of spanning tree mechanism and TPSN on schedule-based algorithms GCF, A-DRAND and proposed SDA. The average energy saving is improved by 41.45%, 40.01% and 42.40% as compared to TPSN and shown in Figure 5-4(c). This variation in energy is due to the unbalanced clock of node and reference clock of the network. In the case of SDA, level-by-level synchronization diminishes the effect of time drift, while TPSN considers the synchronization of nodes and network once.

Average Throughput and Delay: It depends on the time required to synchronize the clock of the node at lower level and reference node clock. With consideration of minimum drift due to level-by-level synchronization, throughput and delay improve by 27.37% and 3.15% respectively as shown in Figure 5-4(d) and (e). The hybrid synchronization in SDA improves the throughput due to the allocation of conflict-free scheduling slots, and these slots are synchronized to transfer the aggregated packets. At the outset, SPT is more prominent than TPSN.

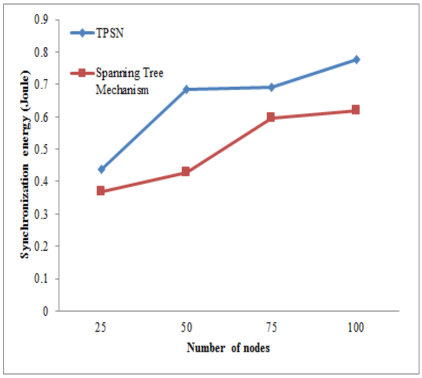
5.4.2. RESULTS WITH STATIC SINK AND FIXED NODE MOBILITY: BESDA [11]

This section provides the analysis by considering the effect of fixed mobility of nodes with static sink. The proposed Bandwidth efficient Hybrid Synchronization for Wireless Sensor Network (BESDA) [11]. With the increase in fixed mobility (20 meters/sec) of the node [28] the control messages required to communicate the location increases but improves the throughput and delay and energy consumption [11]. The node mobility in a WSN can be classified according to the mobility subject, nature of mobility and available data.

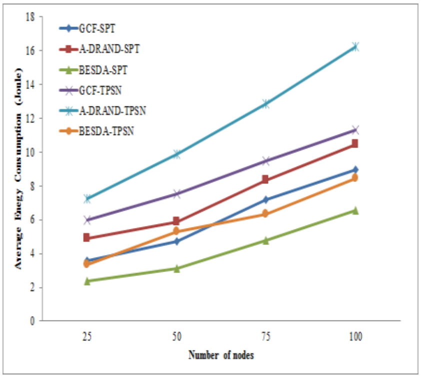
Sync errors and sync energy consumption: The synchronization errors are due to mismatch of the global clock of the sink and local clock of the nodes. It is represented by the clock skews. With the mobility of nodes, the clock skews are increased with increase in sync errors and energy consumption required for the synchronization [11]. The synchronization errors are reduced by 17.30% and average energy consumption by 22.32% as shown in Figure 5-5 (a) and (b) respectively. As compared to static sink it is increased, since the mobility of nodes frequently changes the network dynamics.



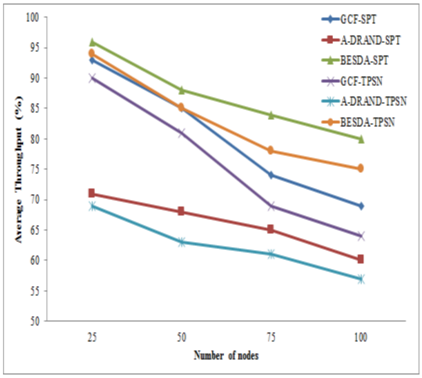
(a)Sync errors-BESDA



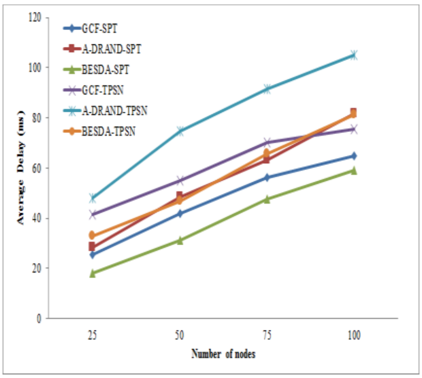
(b)Sync energy consumption-BESDA



(c)Energy consumption-BESDA



(d) Throughput-BESDA



(e) Delay-BESDA

Figure 5- 5 Results with node mobility- BESDA [11]

Average Energy Consumption: Figure 5-5(c), shows the average energy consumption of BESDA, GCF, A-DRAND and with TPSN and SPT mechanism. With the application of SPT and Hybrid synchronization mechanism the energy consumption of BESDA is 27.80%, 28.68% and 35.99%. It shows that hybrid synchronization with SPT mechanism consumes less energy as compared to TPSN. This causes due to shifting of the level of mobile nodes in the allocated time slots and mismatch of node clocks with parent in intra-cluster operation. In TPSN based synchronization, clocks of an individual node are synchronized with a reference clock at a time. Also, nodes have to give their larger share of energy to reduce synchronization errors.

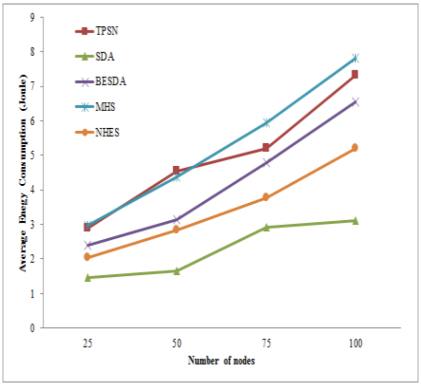
Average Throughput: Figure 5-5(d) the average throughput of proposed BESDA is compared with SPT and TPSN mechanism applied on the scheduling algorithm GCF, and A-DRAND used to collect and schedule the packets from three and two hops respectively. With the application of SPT mechanism throughput increases by 4.59%, 5.29% and 2.32% in BESDA, GCF and A-DRAND as compared to TPSN. If we compare with SPT mechanisms of GCF, A-DRAND and BEASD throughput of BESDA is improved by 7.75% and 24.13% respectively. The mobility of node increases the possibility of one-hop and two-hop weights in the respective level. Also, the position of node changes and takes more time to take the decision in TPSN-based synchronization mechanism, causing reduced throughput.

Average Delay: Figure 5-5(e), shows trends of average delay of SPT and TPSN mechanism with hybrid nature. With proposed SPT mechanism and level-by-level synchronization time drift is reduced and shows reduced delay of 17.21% and 6.33% in scheduling and synchronizing the packets as compared to GCF and A-DRAND. Also, the time required for matching clocks of the mobile node and corresponding parent for transfer of packets to the upper layer is reduced.

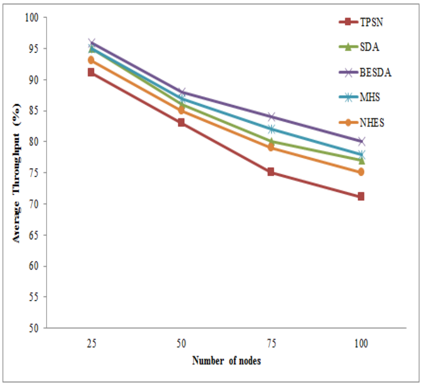
In all the cases, A-DRAND shows the lowest performance as compared to SDA, BESDA, and GCF due to the randomized schedule and single synchronization time to all nodes. Also, proposed SPT mechanism working on level-by-level synchronization has reduced synchronization errors, delay, average energy consumption, and improved throughput as compared to TPSN in the network with static and mobile nodes.

5.4.3. A HYBRID SYNCHRONIZATION ALGORITHM: MHS AND NEHS

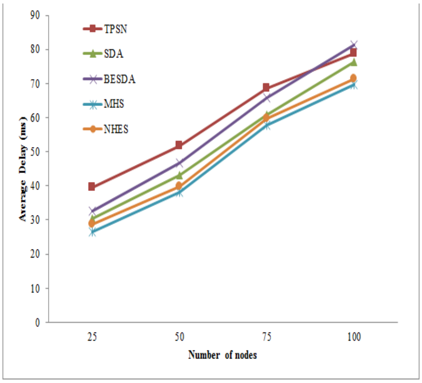
The energy of the node in the WSNs is scarce and causes variation in the lifetime of the network. Also, the throughput and delay of the network depend on how long the network sustains i.e. energy consumption. One way to increase the sustainability of network for improving bandwidth utilization and energy is the addition of heterogeneous nodes regarding energy [12-14], and the other is to use the slotted transmission schemes that allow nodes to regularly schedule the activities according to the required priority [30, 31]. Such scheme requires the synchronization mechanisms to setup and maintain the transmission schedule. It is possible by synchronizing node's clock with the reference clock of the parent node in the network. This section discusses effects of added node heterogeneity along with slot synchronization on the improvement of energy consumption and bandwidth utilization. The nodes in the cluster and CHs in the network are synchronized with the global time scale of the network. The energy consumption and delay in NHES [13] is minimized by synchronizing the time slots allocated using TDMA based MAC protocol. The results show that hybrid approach helps to improve the throughput (bandwidth utilization), energy consumption with less delay as compared to the results obtained in the previous section 5.4.1 and 5.4.2.



(a)Energy consumption-NHES



(b)Throughput-NHES



(c)Throughput-NHES

Figure 5- 6 Results with node mobility and heterogeneity- MHS/NHES [12,13]

Average* Energy *Consumption: In Figure 5-6(a) NHES shows less energy consumption as compared to TPSN, BESDA, and MHS (30.66%, 18.01%, and 34.44% respectively) but more than SDA. This is due use of network- wide clock for nodes, while NHES uses level-by-level node synchronization mechanism. The clustered tree architecture does not require to transmitting the message for long distance hence saves energy. Also, BESDA and MHS uses the fixed and random mobility of the nodes, which requires more energy for message exchange in the formation of the tree, since the mobility of nodes frequently changes the network structure and consumes energy. In the NHES the nodes added with controlled heterogeneity and re-election of CH is avoided this saves the energy and sustains the network for a long time.

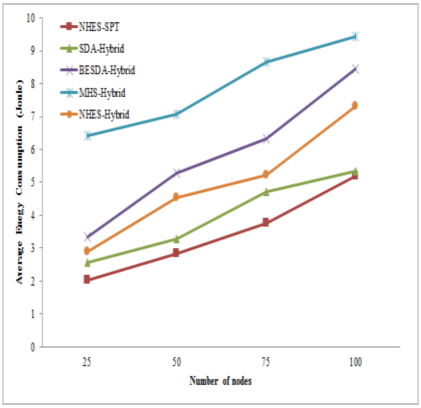
Average Throughput: Figure 5-6(b), shows a comparison of average throughput measured at the sink. The average throughput of SDA, BESDA and MHS is greater (1.76%, 4.59%, and 2.92%) than the NHES. The reason is that the mobility of nodes in the network increases the probabilities of one-hop neighbors to transmit the aggregated packet. By adding controlled heterogeneity, the network remains operative even though some nodes die early. Also, the synchronizing the clocks of parent and child node level-by-level show improvement in throughput of NHES as compared to TPSN.

Average Delay: Figure 5-6(c) shows the delay that causes in the transmission of packets from nodes to CH to sink. With the introduction of controlled heterogeneity of nodes, an average delay is reduced by 16.40%, 5.35 % and 11.94% with SPT as compared to TPSN, SDA, and BESDA, since network sustains for a long time. Due to random nature, the time drifts introduced in TPSN take increased time to make the scheduling decision as compared to NHES. Also, the time required for retransmission is increased due to mismatch and increased clock skews. The overheads in the network are the main reasons of increased delay and reduced throughput in case of TPSN.

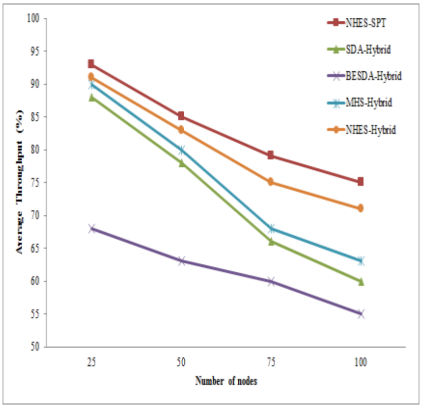
Average Energy Consumption–Hybrid: The average energy consumption of the NHES after application of the scheduling and synchronization algorithm is reduced by 14.62% and 36.77% as compared with BESDA and MHS. However, higher than SDA and NHES with SPT. The basic reason is BESDA and MHS operates on the mobility of nodes, which takes more time to decide the schedule and then synchronize as shown in Figure 5-7(a). The hybrid approach also helps to reduce the clock skews and routing overheads from the node at lower level towards root hence reduced energy consumption.

Throughput–Hybrid: The hybrid approach used in the NHES improves the packet delivery ratio hence throughput. Due to the proper balancing of slots and maintaining the active period of the nodes time is saved. Also, according to the adjusted time slots and synchronizing the clocks of the nodes and network level by the throughput of

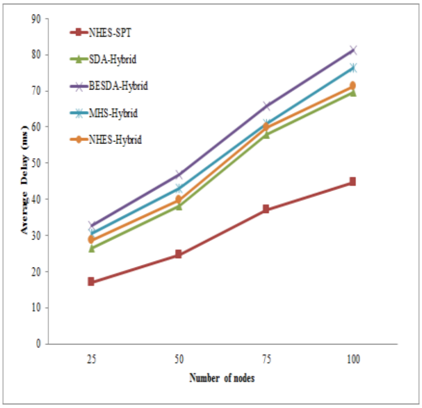
NHES is increased by 4.5%, 9.58% and 30.08% as compared with SDA, BESDA and MHS as shown in Figure 5-7(b). In the case of MHS and BESDA, some control overheads are increased which takes more time for the node to schedule and synchronize. The increased throughput is the measure of bandwidth utilization.



(a) Energy consumption-Hybrid



(b) Throughput-Hybrid



(c) Delay-Hybrid

Figure 5- 7 Hybrid synchronization algorithm [14]

Average Delay–Hybrid: Figure 5-7(c), shows the average delay after application of hybrid mechanism on the NHES and other algorithms. Due to reduced clock skews and retransmission of messages for synchronizing the slots and nodes in the present level reduces the delay in the transmission of packets. The delay of NHES with hybrid approach is less by 11.94%, and 5.35% as compared with BESDA and MHS, but is more as compared with SDA.

5.5. SUMMARY OF CHAPTER

Chapter evaluates the performance of the hybrid synchronization algorithms in static, mobile and heterogeneous scenarios of the network. Slot allocation using TDMA scheduling and level-by-level synchronization of nodes in the network using SPT mechanism reduces the delay, average energy consumption with increased throughput and a lifetime of the network. It also reduces the errors occurring due to mismatch of nodes clock with the reference clock of the network. In the proposed SDA [10], the synchronization errors are reduced by 9.86% with sync energy saving of 21.49% as compared to the randomized algorithm (TPSN). The hybrid synchronization algorithm (BESDA) [11] improves performance by a factor of 3%. Also, the algorithms using node mobility and heterogeneity (MHS and NHES) [12-13] with SPT mechanism shows improvement in throughput (bandwidth), delay, and has reduced energy consumption (29.32%). With the introduction of random node mobility and heterogeneity (NHES) [13-14], the performance of the synchronized algorithm is improved by 4%. The reduced clock skews and improvement in throughput is the indication of better energy saving and bandwidth utilization.

5.6. REFERENCES

[1] Bharath Sundararaman, Ugo Buy, and Ajay D. Kshemkalyani, “Clock synchronization for wireless sensor networks: a survey,” Elsevier Ad Hoc Networks vol. 3, pp. 281–323, 2005.

[2] Erchin Serpedin and Qasim M. Chaudhari. “Synchronization in Wireless Sensor Networks: Parameter Estimation, Performance Benchmarks, and Protocols,” Cambridge University Press, New York, NY, USA, 2009.

[3] Saurabh Ganeriwal Ram Kumar, and Mani B. Srivastava, “Timing-sync Protocol for Sensor Networks,” SenSys’03, pp..1-12, Nov. 2003.

[4] Ruggero Carli, Giada Giorgi, Claudio Narduzzi, “Comparative analysis of synchronization strategies in a sensor network with misbehaving clocks,” 2012 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), pp. 2617-2622, May 2012.

[5] Na Wang, and Yan Xia Pang, “Time Synchronization for Wireless Sensor Network Based on Major Clock,” The 7th International Conference on Computer Science & Education (ICCSE 2012), pp. 295-298, July 2012.

[6] LI-Ming He, “Time Synchronization Based on Spanning Tree for Wireless Sensor Network,” IEEE Wireless 4th International Conference on Communication, Networking and Mobile Computing, WiCOM’08, pp. 1-4, 2008.

[7] Huang Hai-ping, Wang Ru-chuan, Liu Li, Sun Li-juan, Li Wen-feng, "Time synchronization algorithm of wireless sensor networks based on data aggregation tree," vol 17, pp. 24–29, July 2010.

[8] Dnyaneshwar S. Mantri, Pranav Pawar, Neeli Rashmi Prasad, and Ramjee Prasad, "An Efficient Schedule based Data Aggregation using Node Mobility for Wireless Sensor Network," Wireless Vitae 2014, pp.1-5, May 2014.

[9] Wu Yanwei, Li Xiang-Yang, Liu YunHao, and Lou Wei, "Energy-Efficient Wake-up Scheduling for Data Collection and Aggregation," IEEE Transactions on Parallel and distributed systems, 21(2), pp. 275-287, Feb. 2010.

[10] Dnyaneshwar S. Mantri, Neeli Rashmi Prasad, and Ramjee Prasad, "Synchronized Data Aggregation for Wireless Sensor Network," 1st IEEE Global Conference on wireless computing and networking, pp. 263-267, Dec. 2014.

[11] Dnyaneshwar S. Mantri, Neeli Rashmi Prasad, and Ramjee Prasad, "Bandwidth Efficient Hybrid Synchronization for Wireless Sensor Network," 4th International Conference on Advances in Computing, Communications and Informatics (ICACCI2014), pp. 2108-2013, Aug. 2014.

[12] Dnyaneshwar S. Mantri, Neeli Rashmi Prasad, and Ramjee Prasad, "Mobility-aware Hybrid Synchronization for Wireless Sensor Network," WPMC- 2015, Hyderabad, India (Presented).

[13] Dnyaneshwar S. Mantri, Neeli Rashmi Prasad, and Ramjee Prasad, "Node Heterogeneity for Energy Efficient Synchronization for Wireless Sensor Network," 7th International Conference on Communication, Computing and Virtualization (ICCCV-16), in association with Elsevier B.V. Amsterdam, Procedia Computer Science vol 79, pp. 885-892, Feb. 2016.

[14] Dnyaneshwar S. Mantri, Neeli Rashmi Prasad, and Ramjee Prasad, "Heterogeneity–aware Bandwidth Efficient Hybrid Synchronization for Wireless Sensor Network," Extension of (ICCCV-16) in International Journal of Computer Application (IJCA)- ISSN 0975–8887 (Accepted).

[15] Xi Deng, and Yuanyuan Yang "Communication Synchronization in Cluster-based Sensor Networks for Cyber-Physical Systems," IEEE Transaction on Emerging Topics in Computing, 1(1), pp. 98-110, June 2013.

[16] Yildirim K.S., and Gürcan O. "Efficient Time Synchronization in a Wireless Sensor Network by Adaptive Value Tracking," IEEE Transactions on wireless communications, 13(7), pp. 3650–3664, July 2014.

[17] J. Elson, L. Girod, and D. Estrin, “Fine-grained network time synchronization using reference broadcasts,” Proceedings of Fifth Symposium on Operating Systems Design and Implementation (OSDI 2002), vol. 36, pp. 147–163, 2002.

[18] Kasim Sinan Yildirim and A ylin Kantarci, “External Gradient Time Synchronization in Wireless Sensor Networks,” IEEE Transactions on Parallel and Distributed Systems, 25(3), pp. 633–641, March 2014.

[19] Peter Korteweg, Alberto Marchetti-Spaccamela, Leen Stougie, and AndreaVitaletti “Data Aggregation in Sensor Networks: Balancing Communication and Delay Costs,” pp.1-13, June 2012.

[20] Gopal Chand Gautam1, T. P. Sharma, Vivek Katiyar and Anil Kumar, “Time Synchronization Protocol for Wireless SensorNetworks using Clustering,” 2011 ICRTIT, pp. 417-422, June 2011.

[21] L. Schenato and F. Fiorentin, “Average timesynch: a consensus-based protocol for time synchronization in wireless sensor networks,” Automatica, 47(9), pp. 1878–1886, 2011.

[22] Pranav M. Pawar, Rasmus H. Nielsen, Neeli R. Prasad, Shingo Ohmori, and Ramjee Prasad, “GCF: Green Conflict Free Scheduling Algorithm for WSN,” ICC-E2Nets Workshop, pp. 5795-5799, June 2012.

[23] Abdulaziz Y. Barnawi, “Adaptive TDMA Slot Assignment Using Request Aggregation in Wireless Sensor Networks,” The 3rd International Conference on Ambient Systems, Networks and Technologies (ANT), vol. 10, pp. 78-85, 2012.

[24] Miao Zhao; Ming Ma; Yuanyuan Yang, "Efficient Data Gathering with Mobile Collectors and Space-Division Multiple Access Technique in Wireless Sensor Networks," IEEE Transactions on Computers, 60(3), pp. 400-417, March 2011.

[25] Konstantin Mikhaylov, and Jouni Tervonen, “Energy Consumption of Mobile Wireless Sensor Network’s Node with Controlled Mobility,” 27 IEEE, Conference on Advanced Information Networking and Applications Workshop, pp. 1582-1587, 2013.

[26] Ren, Qianqian; Guo, Longjiang; Zhu, Jinghua; Ren, Meirui; Zhu, Junqing, "Distributed aggregation algorithms for mobile sensor networks with group mobility model," Tsinghua Science and Technology, 17(5), pp. 512-520, Oct. 2012.

[27] Dnyaneshwar Mantri, Neeli R. Prasad, and Ramjee Prasad, "Grouping of Clusters for Efficient Data Aggregation (GCEDA) in Wireless Sensor Network," 3rd IEEE International Advance Computing Conference (IACC-2013), pp. 132-137, Feb. 2013.

[28] C. Bettstetter, G. Resta, and P. Santi. "The node distribution of the random waypoint mobility model for wireless ad hoc networks," IEEE Transactions on Mobile Computing, 2(3), pp. 257–269, July 2003.

[29] Mikhaylo K, Tervonen J, "Energy Consumption of the Mobile Wireless Sensor Network's Node with Controlled Mobility," 27th International Conference on Advanced Information Networking and Applications Workshops (WAINA), pp. 582-1587, 2013.

[30] Nidal Nasser, Lutful Karim, and Tarik Taleb, "Dynamic Multilevel Priority Packet Scheduling Scheme for Wireless Sensor Network," IEEE Transactions on Wireless Communications 12(4), pp. 1448 – 1459, April 2013.

[31] Sarma H K D, kar A, Mall R,"Efficient routing protocol for wireless Sensor Networks with Node and Sink Mobility," 2011 IEEE Sensors Applications Symposium (SAS), pp. 239-243, 2011.

CHAPTER 6. CONCLUSIONS AND FUTURE OUTLOOK

This chapter reviews the research objectives of the thesis and summarizes potential outcomes, highlighting how the research contributions fulfilled the original aims and objectives. This thesis addresses the bandwidth management issues in the WSNs and proposes the framework, methodology to increase its utilization, which is one of the important performance metrics for transfer of data in WSN. A framework for data aggregation-Cluster-based network with perfectly compressible aggregation function to reduce energy consumption and improve bandwidth utilization, scheduling algorithms for conflict-free slot allocation based on the myopic and non-myopic state of the channel for improvement of throughput, and synchronization of the local clock of the node and global clock of the network using SPT as part of bandwidth management framework is proposed, discussed and validated with use cases. The WSN network is formed with statics, mobile, and heterogeneous nodes for performance evaluation. Throughout the thesis, the proof of concept and simulation results are presented to validate the finding. Finally, the chapter concludes with the future outlook.

6.1. SUMMARY OF CONTRIBUTIONS

The research work presented in this thesis has identified some of the important challenges for bandwidth management in WSNs. These challenges are addressed by different techniques to improve the energy and bandwidth utilizations. The results are compared with the existing methods showing better performance. The detailed summary and findings of each contribution is given. The chapter also discusses the future outlook for each of the presented contributions.

The focus of chapter 1 is to give an introduction, requirement and a vision for developing an energy efficient bandwidth management mechanism for WSNs. It provides intuition to the motivation, challenges, novelty, contributions, research questions, and methodology followed. The research identified the challenges of WSNs by studying different WSN applications with focus on precision agriculture and health care monitoring. Energy, delay, throughput, communication bandwidth, scalability, lifetime, heterogeneity and mobility support are the major challenges identified from the research with existing mechanisms. The chapter surveys different techniques to improve the energy efficiency and throughput regarding bandwidth utilization and proposed a new bandwidth management mechanism based on identified challenges and is shown in Figure 1-3 and 1-4. The bandwidth management framework has three major blocks: 1. Aggregation, 2. Scheduling mechanisms and 3. Synchronization mechanism. The challenges are charted with these three major blocks to develop an efficient bandwidth management framework by considering static, mobile and heterogeneous scenarios. It helps to understand the flow and development of different stages of the research.

The data processing in the WSNs is effectively represented by the process of aggregation to improve the energy efficiency, throughput and lifetime. The proposed algorithms in chapter 2 work on the two aggregation levels as intra and inter-cluster aggregation. The rate-based perfectly compressible aggregation function applied on packets by considering the semantic and temporal correlation at CH and sink shows a considerable saving in bandwidth utilization; it improves the network lifetime and communication cost. The proposed TTCDA shows energy saving of 14.21% when rate of packet generation is diverse. Also, the concept of grouping the nodes at intra-cluster and CHs at inter-cluster aggregation and communication (GCEDA) shows the reduced energy consumption by 14.94 %. But, if network diameter increases it is increased approximately by 1%. The cluster-based network are used in WSN for data aggregation which gives best results for a scalable network with minimum variations in topology and energy consumption as compared to the tree-based network. The perfectly compressible aggregation function helps to improve the computation and communication cost but has reduced reliability. The outcome of this chapter shows that the proposed data aggregation method is useful to improve energy consumption; delay, throughput, and network lifetime by confirming the hypothesis made in 1.5.1-a. The results also give the motivation to develop the lightweight protocol to reduce the energy consumption in the mobile muti-level scenario.

The mobility and heterogeneity of node and sink are the important factors that need to be considered in WSNs since mobility frequently changes the network dynamics incurring overheads. Chapter 3 survey the different mobility requirements of the WSN and develops the network model used for the aggregation. It considers the fixed region for aggregation with added heterogeneous nodes and mobile sink for effective utilization of communication bandwidth and reduced energy consumption. With the addition of the heterogeneous nodes in the network, the lifetime of the network increases. The proposed algorithm [BECPA, BECDA, MHBCDA, and BHCDA] uses the perfectly compressible aggression function on the packets generated at a variable rate and random data in the range of 0 and 1. According to the results of with and without the mobility of sink, the performance measure such as PDR and throughput reduces showing the effective utilization of bandwidth as compared to EECDA. It happens due to the elimination of repetitive data from the nodes. With the addition of heterogeneous nodes with static sink (BECPA) shows better energy saving (4.47%), reduced throughputs (55.18%) and packet delivery ratio (58.69%) as compared with data aggregation and EECDA. MHBCDA uses the network with heterogeneous node and mobile sink for packet aggregation. It has better energy saving (4.11%), improved network lifetime (34.45%), and reduced throughputs (68.05% &72.95%) in ER and DR of packet generation as compared with EECDA. BHCDA works on the data within the packets generated by use of a random function with heterogeneous nodes and mobile sink. BHCDA shows improvement in throughput hence Bandwidth efficient as compared to TTCDA. The addition of heterogeneous nodes and providing mobility to sink, the performance of the network improves with communication cost, bandwidth utilization, and a lifetime of the network with reduced energy consumption by confirming the hypothesis made in 1.5.1-a &b. The packet aggregation is effective than data aggregation for efficient use of energy and bandwidth utilization. The critic is with increased number of nodes, traffic interval and mobility to sink, the energy consumption increases and possibility of increased collision between packets with more consumption of bandwidth.

The energy consumption, delay and throughput are prime importance in the scheduling algorithms, which are affected by the collision of data/packets transferred from nodes to CH and sink at the same time through multipath. Scheduling algorithms are required for finding efficient schedules to allocate conflict-free slots for nodes and CHs to communicate. It is an important building block for efficient bandwidth utilization mechanism. Chapter-4 describes the classification of different scheduling algorithms based on the static and mobile nodes and sink in the network. It uses the conflict-free scheduling for collision avoidance, energy efficiency, and improvement in throughput. The research proposes new scheduling algorithms based on the myopic and non-myopic state of the channel. Algorithms are expedient for allocating the schedules based on TDMA as basic MAC layer protocol, availability of channel and number of packets in the intra and inter-cluster communications. In the sequel, the chapter has four contributions: first, Cluster based Myopic Scheduling (CMNS) algorithm- based on the static node and sink. Second, an Efficient Schedule-based DA using Node mobility (SDNM) algorithm minimizes the collision of packets in the channel. The slot allocation for transfer of aggregated packets is on the basis of present and predicted future state of the channel. Third, Cluster based Myopic and Non-myopic Scheduling (CMNMS) algorithm- based on the sink mobility. From the simulation results and discussion in section 4.5, it confirms that performance of scheduling algorithms is improved by reducing the number of conflicts, energy consumption, delay and an increase in throughput with CMNMS as compared to CMNS and SDNM. The last contribution of the chapter is Scheduled Collision Avoidance (SCA) algorithm - A hybrid approach of scheduling is used for reducing the collisions by combination of CSMA and TDMA scheduling algorithms. It adjusts the sleep/wake-up time of the node and CHs for transfer of packets to sink according to free slots. The outcome of this chapter shows that the proposed scheduling algorithm reduces the number of conflicts in allocating the slots, reduces the energy consumption, and improves the network lifetime with increased throughput by confirming the hypothesis made in 1.5.1-C. The proposed myopic and non-myopic scheduling approach shows scalable performance in network scenarios with static, and mobile nodes and sink as compared with state-of-the-art solutions.

Time and clock synchronization algorithms are important for managing the schedules in WSN. Chapter-5 addresses the synchronization issue in WSN by considering static, mobile and heterogeneous scenarios of nodes. It works on the formation of cluster-based spanning tree mechanisms. The proposed level by level synchronization of the clocks used by node and network helps to reduce synchronization errors, clock skews, and the energy required to synchronize the slots and improves the throughput. The chapter also proposes the hybrid synchronization algorithm, where scheduling algorithms are used to schedule the slots and synchronization algorithm to synchronize them. The chapter has four contributions 1). Synchronized Data Aggregation (SDA): works on static nodes and sink, proposed "SPT mechanism reduces the synchronization energy by 21.49% and errors by 9.86 % as compared to TPSN and GCF". 2) Bandwidth efficient SDA (BESDA): It considers the mobile nodes in the network. Slots are scheduled and synchronized with the notion of global time scale to improve the lifetime, reduced synchronization error (17.30%) that occurs due to the improper balancing of the clock, reduced energy consumption by 22.32%, and increased throughput (19.28%). With node mobility performance of the BESDA is improved by a factor of 3%. 3) The proposed mobility-aware hybrid synchronization algorithm with heterogeneous nodes (MHS and NEHS) reduces the clock drifts and hence errors which result in an increase of the throughput (21.54%), and reduces the delay. It also reduces the energy consumption by 29.32%. With heterogeneity and random node mobility, the performance of NHES is improved by 4%. The Hybrid approach of scheduling and synchronization reduces the energy consumption, minimizes the delay and increases the throughput as compared with the state-of-the-art solutions confirming hypothesis made in 1.5.1-d, hence clock and time synchronization is prime in the WSN for reducing the errors in collaborative and coordinated communication of packets in the network.

At the outset, the thesis proposes the new framework for bandwidth management in the WSNs using aggregation, scheduling and synchronization with reduced complexity. The proposed solutions are lightweight and enable to enhance the applicability to increased application domain of WSNs.

6.2. FUTURE SCOPE

There is always a scope to improve it and enhance the work for better applicability. The addressed research problem on bandwidth management of WSN will be enhanced in following ways,

- The research proposed the bandwidth management framework and framework; this framework will be enhanced to improve the energy efficiency for real-time applications by considering cross-layer approach and development of lightweight coding, cryptography, and security for increasing the reliable data communication by reducing the redundancy.

- The presented bandwidth management framework can be applied to the IoT use cases. It will directly effect on the high level of interconnections between things and services in real time.

- The presented framework can be extended by actual implementations in the vehicular network which has the prime importance of bandwidth utilizations.

- The thesis concentrates on modeling and development of countermeasures by considering aggregation of packets and data at upper layers and can be extended to all layers of WSN protocol stack.

- The solution developed in thesis considered one or two cross-layer features for effective utilization of bandwidth in terms of throughput. The better solution will be developed by considering multi-cross layer features of physical and MAC layer.

- The proposed framework can be extended for different topological variation of network considered as a hybrid approach for stable results.

- The major issue of scheduling and synchronization can be extended by considering the graph theory and information theoretic approach.

APPENDICES

Appendix A. Contributions towards chapters

Sr. No.	Publications	Chapters				
		Chap-1	Chap-2	Chap-3	Chap-4	Chap-5
1	Two Tier Cluster-Based Data Aggregation (TTCDA) in Wireless Sensor Network		√			
2	BECPA: Bandwidth Efficient Cluster-Based Packet Aggregation in Wireless Sensor Network		√			
3	BECDA: Bandwidth Efficient Heterogeneity aware Cluster based Data Aggregation for Wireless Sensor Network			√		
4	Mobility and Heterogeneity-Aware Cluster-based Data Aggregation for Wireless Sensor Network			√		
5	Heterogeneity–aware Bandwidth Efficient Hybrid Synchronization for Wireless Sensor Network					√
6	Two tier cluster based Data Aggregation (TTDCA) for Wireless Sensor Networks		√			
7	Grouping of Clusters for Efficient Data Aggregation (GCEDA) in Wireless Sensor Network		√			
8	BECPA: Bandwidth Efficient Packet Aggregation for Wireless Sensor Network			√		
9	MHBCDA: Mobility and Heterogeneity aware Bandwidth Efficient Cluster based Data Aggregation for Wireless Sensor Network			√		

10	BHCDA: Bandwidth Efficient Heterogeneity aware Cluster based Data Aggregation for Wireless Sensor Network			√		
11	Cluster-based Myopic and Non-myopic Scheduling for Wireless Sensor Network				√	
12	An Efficient Schedule based Data Aggregation using Node Mobility for Wireless Sensor Network				√	
13	Scheduled Collision Avoidance in Wireless Sensor Network using ZigBee				√	
14	Synchronized Data Aggregation for Wireless Sensor Network					√
15	Bandwidth Efficient Hybrid Synchronization for Wireless Sensor Network					√
16	Mobility-aware Hybrid Synchronization for Wireless Sensor Network					√
17	Node Heterogeneity for Energy Efficient Synchronization for Wireless Sensor Network					√

ISSN (online): 2246-1248
ISBN (online): 978-87-7112-702-7

AALBORG **UNIVERSITY PRESS**